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The microbial quality and the use of sodis to treat harvested rainwater in rural areas of Uganda case study: Makondo-Lwengo Masaka

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THE MICROBIAL QUALITY AND THE USE OF SODIS TO TREAT HARVESTED RAINWATER IN RURAL AREAS OF UGANDA
CASE STUDY: MAKONDO-LWENGO MASAKA

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NEA ONNIM NO SUA A, OHU

"HE WHO DOES NOT KNOW, CAN KNOW FROM LEARNING"*

*Akan Adinkra symbol of knowledge, life-long education and continued quest for knowledge.

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DEDICATION

This book is dedicated to my parents (Mathius Kyeswa & Monica Nabankema Kyeswa), my daughters (Astrid Ayebale and Late Aline Arinde) plus friends and family.

DECLARATION

I declare that this thesis, which I submit to RCSI for examination in consideration of the award of a higher degree of **Doctor of Philosophy,** is my own personal effort. Where any of the content presented is the result of input or data from a related collaborative research programme this is duly acknowledged in the text such that it is possible to ascertain how much of the work is my own. I have not already obtained a degree in RCSI or elsewhere on the basis of this work. Furthermore, I took reasonable care to ensure that the work is original, and, to the best of my knowledge, does not breach copyright law, and has not been taken from other sources except where such work has been cited and acknowledged within the text.

Signed ____________________

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LIST OF ABBREVIATIONS

%- Percentage

&-And

ADWG- Australian drinking water guidelines

APHA- American Public Health Association

ATCC- American Type Culture Collection

BGTR - Borosilicate glass tube reactor

C. perfringens- Clostridium perfringens

CBM - community based management

CCA-ChromoCult Coliform agar

CDAs–Community Development Assistants

CDOs–Community Development Officers

CFU-Colony forming units

CLSI- Clinical and laboratory standards institute

cm- Centi metre

CPC-Compound parabolic collector

DEA- Directorate of Environment Affairs

DESS- Department of Environment Support Services

DKIT- Dudalk Institute of Technology

DLC- Diamond-like carbon

DLGs- District Local Governments

DOM- Department of Meteorology

DRA–Demand-Responsive Approach

DWD- Directorate of Water Development

DWOs–District Water Officers

DWRM-Directorate of Water Resources Management

DWSCCs- District water and sanitation coordination committees

DWSDCG- District Water and Sanitation Development Conditional Grant

E. coli- Escherichia coli

EAWAG- Swiss Federal Institute of Environmental Science and Technology

ENR SWG- Environment and Natural Resources Sector Working Group

EU- European Union

FSSD- Forest Sector Support Department

GoU-Government of Uganda

HAs–Health Assistants

HOs– Health Officers

HPC- Heterotrophic plate count

HRW- Harvested rain water

HWTS-Household water treatment and safe storage systems

I.e- That's to say

ICRAF- International council for research in Agroforestry

IDMs- Inter district meetings

IMF-International Monetary Fund

ISO-International Standards Organisation

Km- kilo metre

LGs- Local Governments – Districts, Municipal/Town Councils and counties

log- Logarithm
LRV- log_{10}-unit removal values

m^3 -cubic meters

MAAIF- Ministry of Agriculture, Animal Industry and Fisheries

MAM-March, April and May

MDG- Mellenium development goals

MDG-Millennium Development Goals

MFPED-Ministry of Finance, Planning and Economic Development

mg/l- milligrams per liter

MGLSD–Ministry of Gender, Labour and Social Development

MH–Ministry of Health

ml- Milliliter

MLG-Ministry of Local Government

mm- millimeter

MMM-Medical Missionaries of Mary

MOH-Ministry of Health-Uganda

MPS–Ministry of Public Service

MWE-Ministry of Water and Environment

NEMA- National Environment Management Authority

NFA-National Forest Authority

NGOs- Non-Governmental Organizations

NTU- Nephlometric Turbidity Unit
NWSC-National Water and Sewerage Cooperation

O&M–Operation and Maintenance

°C- Degrees celcius

PET- Polyethylene Terephthalate

PMC- Policy and Management Committee – for the water sector

RCSI- Royal College of Surgeons in Ireland

RWSSD- Rural Water Supply and Sanitation Department

SANDEC- Department of water and sanitation in developing countries at EAWAG

Si-DLC- Silicon doped diamond-like carbon

SODIS- Solar water disinfection

SON-September, October and November

TDS- Total dissolved solids

TPCs- Technical planning committees

TSC- tryptose sulfite-cycloserin agar

TSUs- Technical Support Units – for the water sector

TTC-Thermotolerant coliforms

UBOS-Uganda Bureau of Statistics

Ug shs-Uganda shillings

UgShs- Ugandan shillings

UNBS-Uganda National Bureau of Standards

UNEP- United Nations Environment Programme

UNICEF- United Nations Children's Emergency Fund
UN-United nations

US $- US dollar

US EPA-United States –Environmental Protection Agency

US- United nations

USA-United States of America

UV- Ultraviolet

UWASNET- Uganda Water and Sanitation Network

UWSSD-Urban Water Supply and Sanitation Department

WASH-Water, sanitation and Hygiene

WFP-Water for production (water for agricultural production and industrial purposes)

WHO- World Health Organization

WIL- Water is Life project

WMD- Wetlands Management Department

WQ-Water quality

WSCs–Water and Sanitation Committees

WSLD-Water Sector Liaison Division

WSSD –Water Supply and Sanitation Department

WSSWG-Water and Sanitation Sector Working Group

WS-Water and Sanitation

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To *God*, who makes all things possible be the glory and honour.

ABSTRACT

While harvested rainwater (HRW) is promoted in rural areas of Uganda, little attention has been given to its quality. The current study was carried out to investigate the quality of HRW in the rural area of Mokondo-Lwengo, Uganda and to determine the effectiveness of solar water disinfection (SODIS) to treat drinking water in rural households. Households with HRW systems of different materials were randomly selected and trained in SODIS treatment using 2 liter PET bottles. Following a preliminary short study over 4 months, a year long study was conducted to investigate any seasonal variation. Physiochemical parameters (temperature, pH and TDS) of the raw HRW were tested on site while the samples for microbial analysis were transported for analysis at Makerere University.

Results showed that the HRW met the required physiochemical drinking water standards. However, of the 462 raw HRW samples, 409 (88.5%) were found to be microbiologically contaminated and unsafe for drinking without treatment. *Clostridium perfringens* was never found.

Lack of cleaning of the HRW systems; the manual abstraction of water due to faulty taps; overhanging vegetation around the HRW systems; the poor condition of drainage of water collection area, season, the number of rainfall events in a month and the amount of rainfall received by a system, were the most significant factors influencing the microbial quality of the HRW.

Following SODIS treatment, the treatment efficiency ranged from 61.2%-100% with the highest treatment efficiencies occurring during the dry months of the year.

When a 25L borosilicate glass tube fitted with a compound parabolic collector (BGTR-CPC) was evaluated, bacterial inactivation to below the limit of detection (<1CFU/100ml.) was obtained in 85% of experiments.

1 INTRODUCTION

1.1 UGANDA AND WATER SUPPLY

Uganda lies in East Africa and is one of the countries located within the Great Lake region. Situated within the Nile Basin, the country is well endowed with significant fresh water resources comprising lakes, rivers, streams and wetlands. The most significant lakes include lakes Victoria, Edward, Kyoga and Albert. Lake Victoria which is the second largest freshwater lake in the world is the principle source of water in Uganda. Of the 68,800km^2 of Lake Victoria's surface area, Uganda occupies 45% while Tanzania and Kenya occupy 49% and 6% respectively (Rugumayo, 2012). Out of the 241,500km^2 of the country's land mass, 36, 280km^2 (15% of the total surface area) is occupied by open water (lakes, rivers, streams) while 30105 km^2 (13%) comprises wetlands (NEMA, 1999).

Water resource is a priority in Uganda, as it directly and greatly impacts the quality of life of the people and productivity of the population (MOH, 1999; MWE, 2009). The total amount of water resource is estimated to be 66 km^3, making Uganda a better country in terms of its capacity in renewable water resources than many other African countries (NEMA, 2008). There is an annual average of 2,800 m^3 of water available per capita of the population. However, water resources are not evenly distributed geographically and temporally. Therefore large areas of the country are threatened by persistent periods of floods and drought (Rugumayo, 2012). The available water resources of the country are also challenged by accelerated depletion and degradation due to a high annual population growth rate of 3.3-3.2% (UBOS, 2006a, UBOS, 2012). Groundwater is limited in yield and extent, it is often contaminated and the amount of ground water abstracted in a given period of time is often greater than the amount of water that is replaced through the natural hydrological cycle. In rural areas where boreholes are often used to supply safe drinking water, they commonly dry up as a result of abstraction exceeding recharge mainly in dry seasons (Rugumayo, 2012). Uganda is still one of those countries with low safe water coverage of 64% in rural areas and 70% in urban areas, as of June 2013 (MWE, 2012, MWE 2013).

Uganda lies on the equator with an equatorial climate, is moderately humid and with hot conditions throughout the year. The country has two alternating seasons that are two rainy and two dry seasons in a year. The two rainy seasons are March-May and October -December with the wettest areas along the western shore of Lake Victoria and the north regions of the country being much more arid (NEMA, 1999). The country's economy depends on agriculture and Uganda's climate offers great potential for food production. However, the climate has changed, threatening the country's economy. The climate of Uganda is now characterized by prolonged and frequent drought as well as floods. This impacts on the food supply and water resources, which are known to play a pivotal role on sustainable development and poverty reduction in Uganda (MAAIF report, 2008). Most of the developing countries are termed water-scarce countries which are characterized by low erratic rainfall, which results in high risk of droughts, intra-seasonal dry spells and frequent food insecurity due to dependence on rainfed agriculture (Ngigi, 2003). Uganda is one of the countries which receives intensive rainfall events, which are often convective storms, with very high rain intensity and extreme spatial and temporal rainfall variability (NEMA, 1999). On average Uganda receives about 1217mm of rainfall per year however, this varies widely throughout the country. The semi-arid areas of North East-Kotido receive about 700mm while the Islands of the Kalangala district in Lake Victoria and the slopes of Mt. Rwenzori receive over 1500mm and 2000mm, respectively (NEMA, 1999).

Two-thirds of Uganda receives rainfall in excess of 1200mm per year (NEMA 2002) as shown in Figure 1.1. However, during the rainy seasons 70-85% of the rainfall is reported to be lost through soil evaporation, deep percolation and surface runoff into streams, rivers and lakes (Falkenmark *et al.*, 2001). In such situations rainwater harvesting is a valuable option to ensure water supply during long spells of drought (Helmreich and Horn, 2009).

It was previously estimated that a rainfall of 50mm on a roof area of $15m^2$ would provide 600L of water assuming that the runoff efficiency is 80% (Danert and Motts, 2009). Many regions in Uganda are already harvesting rainwater. Danert and Motts (2009) pointed out that at least 1,250,000 rural households are willing to invest in harvested rainwater (HRW) for domestic use representing substantial opportunities for harvesting rainwater businesses in Uganda.

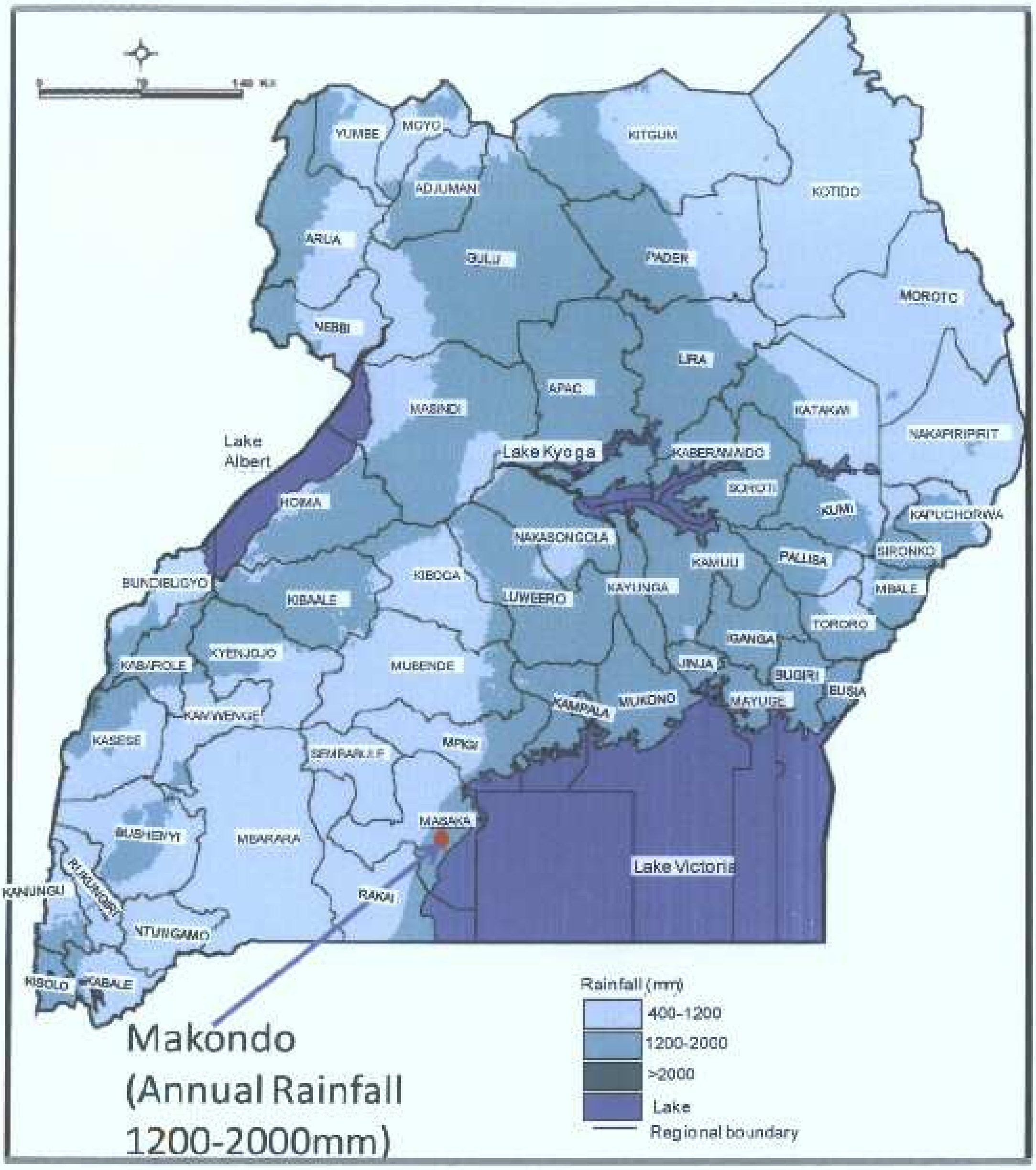


Figure 1.1: The average annual rain fall received in different parts of Uganda (Source: DWRM and meteorology, 2002)

HRW is seen as a viable option for improving water supplies by many sector professionals in Government and by the NGOs, as well as politicians and development partners. Many organizations are financing the construction of HRW infrastructure at household level as well as undertaking promotion efforts (Baguma *et al*., 2010a). Rainfall in most of Uganda is ideal for HRW, with dry spells lasting only to a maximum of four months.

Harvesting rainwater is recommended only for those households in areas with rainfall catchment systems receiving average rainfall greater than 200mm per year. Central Uganda is very suitable since it receives 1200-2000mm per year (Rugumayo, 1995). Infact, based on annual rainfall received, all of Uganda is suitable and could benefit from HRW (ICRAF and UNEP, 2005). Mati *et al.* (2006) recommended HRW as a suitable sustainable intervention for improved access to safe water in dispersed areas where the costs of developing central surface or underground water supply are expensive as is the case for many Ugandan rural households. Therefore, in spite of water quality limitations, HRW is a suitable sustainable intervention to improved safe water access. It is actually reported to be increasingly dominating rural water supply in Uganda to mitigate the water scarcity issues due to climatic change (Sugita, 2006, Baguma and Loiskandl, 2010; Baguma *et al.*, 2010a).

1.2 POLICY AND REGULATION OF WATER QUALITY IN UGANDA

The supply of water in Uganda is controlled by a number of bodies which include the Ministry of Water and Environment (MWE), the Directorate of Water Development (DWD), Rural Water Supply and Sanitation Department (RWSSD) or Urban Water Supply and Sanitation Department (UWSSD) in rural and urban communities, respectively, in addition to the National Water and Sewerage Cooperation (NWSC). Each of these bodies plays a specific role to ensure distribution of safe drinking water to communities. The lead agency for formulating national water and sanitation policies, coordinating and regulating the sector is the Ministry of Water and Environment (MWE). Under the MWE is the Directorate of Water Development (DWD) which acts as the executive arm and provides support to local governments and other service providers.

As far as rural water supply is concerned, the MWE is responsible for setting country-wide policies and standards and has overall responsibility for the management, regulation and development of water resources. It also monitors and evaluates the water resources sector.

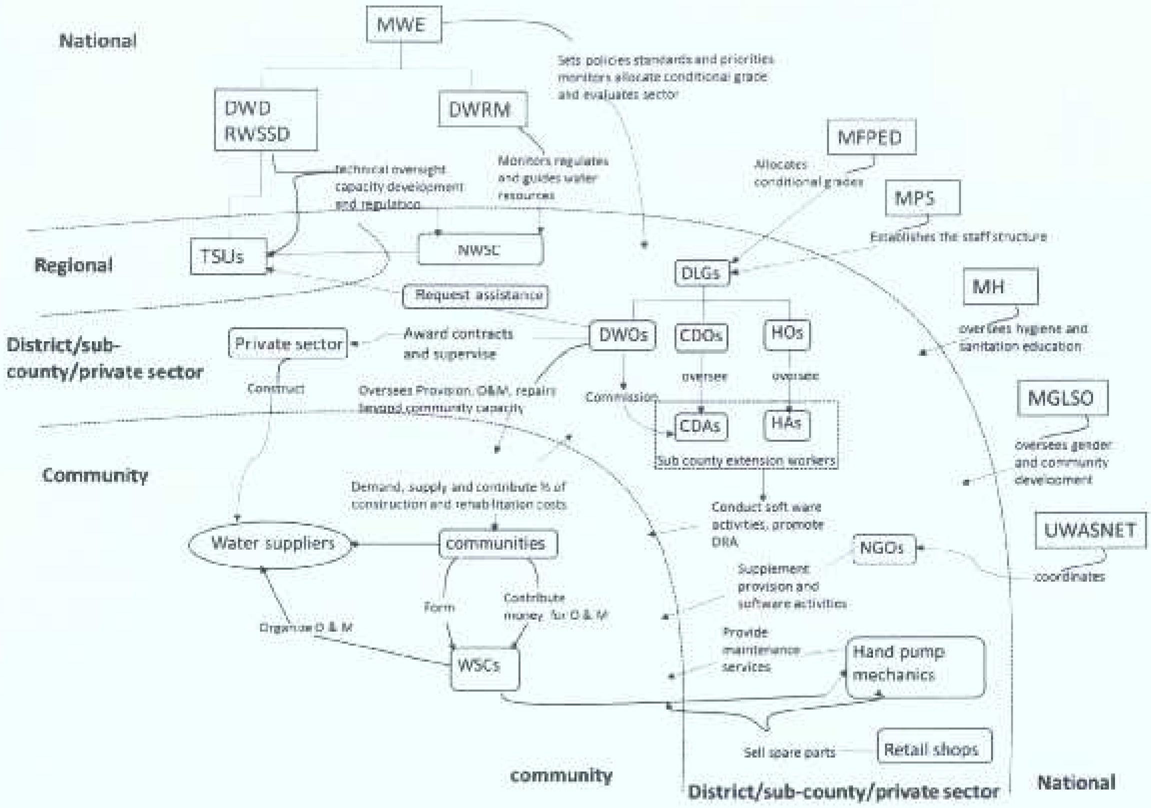


Figure 1.2: The organizational framework for delivery of rural water services in Uganda (Quin *et al*., 2011).

Notes: MWE–Ministry of Water and Environment; DWD–Directorate of Water Development; RWSSD–Rural Water Supply and Sanitation Department; DWRM–Directorate of Water Resources Management; MFPED–Ministry of Finance Planning and Economic Development; MPS–Ministry of Public Service; MH–Ministry of Health; MGLSD–Ministry of Gender, Labour and Social Development; UWASNET–Ugandan Water and Sanitation Network; TSUs–Technical Support Units; DLGs–District Local Governments; DWOs–District Water Officers; CDOs–Community Development Officers; HOs– Health Officers; CDAs–Community Development Assistants; HAs–Health Assistants; NGOs–Non-Governmental Organizations; WSCs–Water and Sanitation Committees; DRA–Demand-Responsive Approach; O&M–Operation and Maintenance

The DWD comprises three departments; RWSSD, the Urban Water Supply and Sanitation Department (UWSSD) and Water for Production department (WFP). The Rural Water Supply and Sanitation Department (RWSSD) is responsible for the delivery of rural water and sanitation services. The RWSSD provides oversight in planning, implementation and supervision of rural water services at the district level and is also responsible for providing capacity development and support to district local governments (DLGs). To better achieve these responsibilities, in 2002 the DWD established eight technical support units (TSUs), each comprised of several consultants specializing in technical or social aspects of delivery, including water and sanitation, public health and community development. TSUs should provide support on a demand-driven basis to a number of DLGs. There are, roughly, two TSUs for each of Uganda's administrative regions (Northern, Eastern, Western, and Central), with each TSU covering approximately 14 districts (111 districts as of 2010). The water tariffs are proposed by National Water and Sewerage Cooperation (NWSC) and are approved by MWE. NWSC is regulated by contract according to a performance contract with the national government (MWE, 2010a).

The Ministry of Finance Planning and Economic Development allocates the District Water and Sanitation Development Conditional Grant (DWSDCG) to DLGs, however, this is determined according to current RWSSD estimates of district water supply coverage (i.e. the percentage of population in a district with access to an improved water supply). The DWSDCG is the main form of Government investment in the rural water programme in Uganda, though a small portion (less than one-tenth) of investments are made directly by the MWE (MWE, 2010b).

The Ugandan Government is using decentralization, allocating increased responsibility to lower levels of government and introducing a "bottom-up" approach to local development planning (GoU, 1997; MLG, 2003a; 2003b). Districts are the highest level of local government in Uganda, which, in rural areas, are further divided up into counties, sub-counties, parishes and villages. The districts in Uganda are assigned to four administrative regions: Northern, Eastern, Western and Central. Local government councils are formed at the district and sub-county levels, each with a chairperson and a number of councilors elected by constituencies within the district or sub-county. Administrative unit councils are formed at the county, parish and village levels. County councils consist of all sub-county executive committees, with district councilors as *ex-officio* members. Parish councils consist of all village officio members. A village council should be comprised of all people over the age of eighteen residing in the village.

The councils with a number of public service committees operating at the various levels of local government have certain roles and responsibilities in local government planning (GoU, 1997; MLG, 2003a; 2003b). DLGs are responsible for the provision of rural water services and their promotion and management (GoU, 1997). Under the supervision of district councils, these activities are undertaken by district water officers (DWOs) (Figure 1.2) and, ideally, several support staff: a hygiene officer, an assistant DWO for community mobilization, one technical officer per county in the district and a borehole maintenance supervisor. DWOs, hygiene officers and assistant DWOs should hold a university degree and have 3years of relevant experience (MWE, 2010b). DWOs participate in district technical planning committees (TPCs), together with health officers (HOs) and community development officers (CDOs). HOs and CDOs may be seconded as District Water Office staff. Sub-county extension workers (HAs and CDAs) play an important role in identifying community needs for both "hardware" (i.e. physical equipment) and "software" (i.e. training for Comminity Based Managers-CBM) and act as a link between DWOs and communities in the delivery of rural water services following the principles of community participation. The extension workers participate in sub-county TPCs and should assist parishes and villages with planning.

A number of water sector committees have been established, and they convene at least once a year. In particular, regional inter-district meetings (IDMs) and district water and sanitation coordination committees (DWSCCs) should be organized. IDMs are organized by TSUs and bring together political leaders, technical officers (DWOs, HOs, and CDOs), NGOs and private sector representatives from a number of districts to discuss experiences, progress reports and plans. It also enables TSUs to explain policy-related issues on behalf of the MWE. The district water and sanitation coordination committees (DWSCCs) should be organized by DWOs and should involve district political leaders, technical officers, NGOs and private sector representatives. The purpose of the DWSCC is to oversee implementation of district programmers and to strengthen collaboration and coordination between actors and sectors within the district.

At community level, the government strategy for the delivery of rural water services should follow the Demand Responsive Approach (DRA) (i.e. DLGs should act in response to community requests for water services). The principles of CBM and community participation are also applied. Thus, communities are expected to form a water and sanitation committee (WSC), contribute part of the capital costs of source development and pay operation and maintenance costs in full. Major rehabilitation costs should be partially covered by the community. WSCs are responsible for managing and banking Operation and Management (O&M) funds collected from users within the community. WSCs should also hire pump mechanics and purchase spare parts when necessary.

Water quality in rural area water sources is monitored by MWE-NWSC. In rural laboratory analysis, database management and reporting of results is done in conformity with WHO guidelines and the National Drinking Water Standards which are a part of Uganda National Bureau of Standards (UNBS). The key parameters reported to director of NWS include pH, colour, turbidity, residual free chlorine and *E. coli* (MWE, 2013). For the case of HRW since it's usually privately owned there is no proper structured body responsible for monitoring its water quality and safety.

1.3 DRINKING WATER

One of the UN Millennium Development Goals is to reduce by half the proportion of people without sustainable access to safe drinking water (United Nations, 2007). In some countries like Uganda, this goal is still not yet assured of being fulfilled by the year 2015. WHO (2012) defines an improved drinking-water source as one that, by nature of its construction or through active intervention, is protected from outside contamination, in particular from contamination with faecal matter. The Government of Uganda defines access to safe water in rural areas as access to water from an improved source within a 1.5 kilometres distance (Danert and Motts, 2009). Using this definition, the Government of Uganda estimated in 2012 and 2013 that 36% of the rural population (about 9.8 million people) was still lacking access to safe drinking water. A number of inhabitants of rural areas in Uganda are still accessing drinking water from unprotected wells and reservoirs (dams) (MFPE-MDG report for Uganda, 2013; MWE, 2012; MWE, 2013; WHO and UNICEF, 2012).

Potable (drinking) water is defined as the water that is safe for human consumption (WHO, 2008). This water should not put a consumer at any risk once it is consumed. The water must have the recommended organoleptic, physical, chemical and microbial characteristics. In Uganda water is said to be safe for drinking (potable) if it conforms to UNBS standards which are similar to WHO (2011) standards. The recommended values for pH and total dissolved solids (TDS) are described in Table 1.1 below. Water is said to be safe for drinking if its pH is in a range of 6.5-8.5 and TDS values are not above 600mg/l.

Table 1.1: Recommended safe drinking water pH and TDS levels by WHO (2011) and UNBS (2009)

Parameter	Required levels	Method of test

Ph	6.5 – 8.5	US ISO 10523
TDS	< 600 mg/ l	Standard Methods for the Examination of Water & Wastewater-APHA (2005)

Like the physiochemical parameters, water to be safe for drinking should also meet the recommended microbial quality. The maximum microbiological limits are detailed in Table 1.2 below. The microbial indicators for example, faecal enterococci, *E. coli* and *C. perfringens* should not be detected in 100ml of the water sample if the water is intended to be taken without any treatment. Although the UNBS drinking water standards are the same as the WHO (2011), UNBS does not state a limit for thermotolerant coliforms (TTC).

Table 1.2: Recommended maximum microbiological limits of safe drinking water

Micro-organism	**Allowable compliance limits**	
	WHO (2011)	**UNBS (2009)**
E. coli (cfu per 100ml)	Not detected	Not detected
Faecal enterococci (cfu per 100ml)	Not detected	Not detected
Thermotolerant coliforms (cfu per 100ml)	Not detected	Not stated
Clostridium perfringens (including viable spores), cfu per 100ml	Not detected	Not detected

Source: UNBS (2009) and WHO (2011)

A number of microbial indicators are recommended in Uganda for assessing the safety of drinking water. These include *E. coli*, faecal enterococci and *Clostridium perfringens*. Indicator bacteria are types of bacteria used to detect and estimate the level of fecal contamination of water. They are not themselves dangerous to health but are used to indicate the presence of a health risk. Coliform bacteria are the most commonly used bacterial indicator for the microbial quality of water (Rompré *et al.*, 2002; Tallon *et al.*, 2005). In assessing the microbial quality of water, it is recommended to use more than one microbial indicator since they vary in survival rates (WHO, 2011; US EPA, 2004).

Escherichia coli (E. coli) and faecal enterococci have been widely studied and used in several studies as indicator organisms for assessing the microbial quality of HRW (Amin and Han, 2009; Sazakli *et al.*, 2007; Radaideh *et al.*, 2009; Karim, 2010). Despite the fact that some studies have shown that *E. coli* multiply in warm, subtropical waters (Byappanahalli and Fujioka, 1998; Desmarais *et al.*, 2002; Solo-Gabriele, 2000; Ashbolt *et al.*. 1997; Bermudez and Hazen 1988; Hardina and Fujioka, 1991; Niemi *et al.*, 1997; Solo-Gabriele *et al.*, 2000), the organism is still the most commonly used bacterial indicator in studying the water quality in both tropical and temperate regions. *Escherichia coli* is known to be present in large numbers in the normal intestinal flora of humans and animals, where it generally causes no harm. It is known to be mainly of fecal origin and can be detected in elevated densities in human and animal feces, sewage and water subjected to recent fecal pollution. WHO (2011) classified *E. coli* as one of the best indicator organisms for faecal pollution. Its guidelines for drinking water quality state that *E. coli* as an indicator organism provides conclusive evidence of recent fecal pollution and should not be detected in any water meant for human consumption. In the U.S., Environmental Protection Agency (EPA) studies have suggested that the best indicators of health risk from recreational water contact in fresh water are *E. coli* and enterococci (US EPA, 2010a). Many studies recommend *E. coli* as a better indicator than use of thermotolerant coliforms (Edberg *et al.*, 2000; Garcia-Armisen *et al.*, 2007; Hamilton *et al.*, 2005; Leclerc *et al.*, 2001; APHA, 2007). Besides *E. coli* being in large numbers in normal intestinal flora of humans and animals, it is easy and relatively cheap to enumerate in laboratories (Hachich *et al.*, 2012). *E. coli* survives in drinking water for between 4 and 12 weeks, however, this largely depends on environmental conditions for example temperature, pH, nutrients and microflora. Among thermotolerant coliforms, *E. coli* forms the largest percentage. It comprises 84.3% of all thermotolerant coliforms (Hachich *et al.*, 2012) which makes it the best indictor organism of all the thermotolerant coliforms.

Feacal enterococci can also be used as an index of faecal pollution. They form a big part of gut commensal microbes in many animals and humans (Farrow and Collins, 1985; Devriese *et al.*, 1990; Hardie and Whiley, 1997; de Vaux *et al.*, 1998; de Graef, *et al.*, 2003; Fogarty *et al.*, 2003; Law-Brown and Meyers, 2003; Koort *et al.*, 2004; Byappanahalli *et al.*, 2012). Many studies have documented the growth of faecal enterococci in sub-tropical and tropical environments (Desmarais *et al.*, 2002; Byappanahalli *et al.*, 2012), it is still widely used (Howard *et al.*, 2003; US EPA, 2004; Haruna *et al.*, 2005; Korajkic *et al.*, 2013). Their abundance in human and animal faeces, the ease with which they are cultured, and their correlation with human health outcomes in fresh and marine waters have led to their widespread use as tools for assessing microbial quality water quality worldwide (Wade *et al.*, 2003; US EPA, 2004; Wade *et al.*, 2006; Wade *et al.*, 2008). Although, the numbers of intestinal enterococci in human faeces are generally lower than those of *E. coli*, enterococci survive longer in water environments than *E. coli* (or thermotolerant coliforms). They are more resistant to drying and more resistant to chlorination (WHO, 2011). Several studies have shown proliferation of classical fecal indicators, for example *E. coli* and faecal enterococci, in tropical waters and thus are detected at levels which do not reflect the original extent of fecal contamination (Carrillo *et al.*, 1985; Desmarais *et al.*, 2002; Jimenez *et al.*, 1989; Perez-Rosas and Hazen.1989; Rivera *et al.*, 1988; Santiago-Mercado and Hazen.1987; Solo-Gabriele, 2000; Valdez-Collazo *et al.*, 1987; Wright, 1989). They have been also suspected to be part of the autochthonous aquatic microbial community in tropical waters (Bermudez and Hazen, 1988; Fujioka and Shizumura.1985; Rivera *et al.*, 1988; Santiago-Mercado and Hazen, 1987). Studies have found high numbers of *E. coli* in the complete absence of any known fecal source (Ashbolt *et al.* 1997; Bermudez and Hazen 1988; Hardina and Fujioka, 1991; Niemi *et al.* 1997; Solo-Gabriele *et al.*, 2000). Because of the unreliability of traditional fecal pollution indicators in tropical conditions, alternative indicator organisms like *Clostridium perfringens* have been recommended to supplement the traditional indicators (Bisson and Cabelli, 1980; Fujioka and Shizumura, 1985; Ahmed *et al.*, 2008; Ahmed *et al.*, 2010). Like *E. coli* and faecal enterococci, *C. perfringens* is a member of the normal intestinal flora of many humans and other warm-blooded animals (WHO, 2011). It is known for producing spores that are extremely resistant to unfavourable conditions in water environments hence surviving longer in aquatic environments than *E. coli* and faecal enterococci. This makes it a suitable indicator organism for faecal contamination which has occurred in the past (Ahmed *et al.*, 2008; Ahmed *et al.*, 2010).

1.4 HARVESTED RAINWATER

Harvesting rainwater (HRW) is reported to have been used for thousands of years (AbdelKhaleq and Ahmed, 2007). Helmreich and Horn (2009) described HRW as a technology where surface runoff is effectively collected during rain yielding periods, whereas according to Lye (2002), harvesting rainwater is defined as the gathering, or accumulating and storing, of rainwater. It is described as a sustainable means for reducing demand at the allotment scale, increasing the regional water security and providing economic benefits to the community (Hatibu *et al.*, 2006; Hartung, 2007).

Harvested rainwater has been highlighted as one of the most appropriate sustainable alternatives for alleviating water scarcity problems and also for providing fresh water at household and community level in order to cope with climatic change (Lye, 2009; Amin and Han, 2009; Hey-Worth *et al.*, 2006; Pathak and Heijnen, 2006). Harvesting rainwater is also one of the ways through which hydrological cycles can be recovered (Kim *et al.*, 2005a) as described in figure 1.3 below.

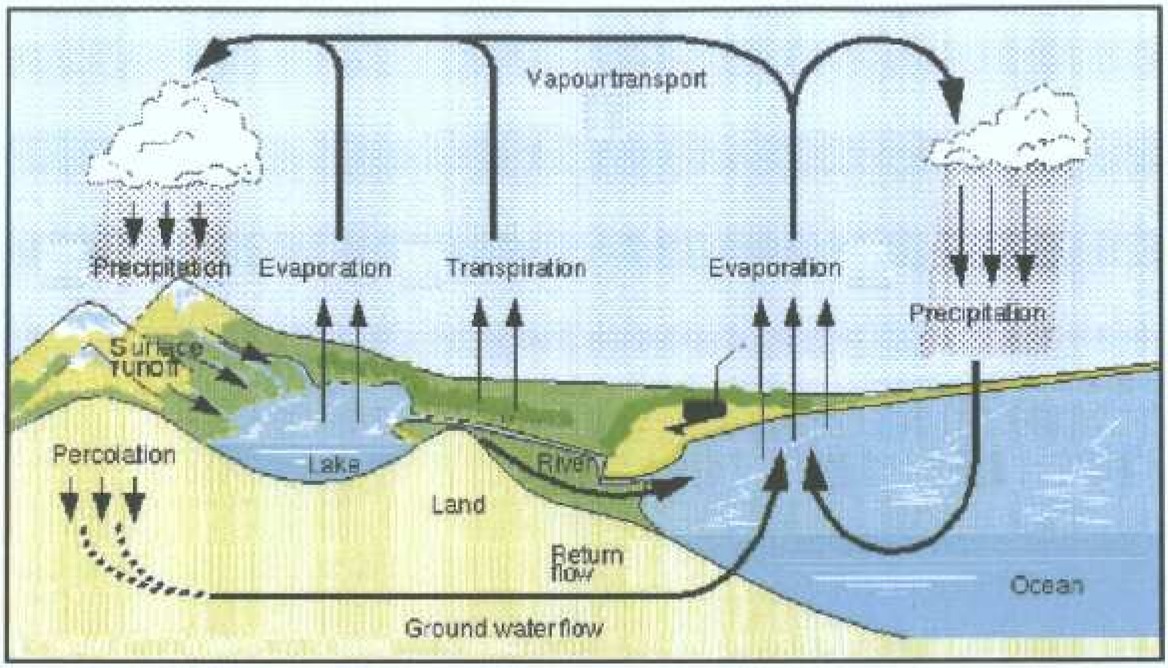


Figure 1.3: The hydrological cycle (source: Google image: http://www.euwfd.com/assets/images/autogen/Image-050202.jpg).

Precipitation is the process that occurs when any and all forms of water particles fall from the atmosphere and reach the ground .precipitated water may fall into a waterbody or it may fall onto land on surfaces like roof tops. From the roof tops it can be collected into containers for various uses.

Many studies have highlighted a number of significant economic, social and environmental benefits of HRW as an alternative water source in rural areas (Hatibu*et al.*, 2006; Hartung, 2007; Sturm *et al.*, 2009). Many rural areas lack traditional centralized water supply systems due to sparsely distributed populations in these regions which makes the cost of installing centralized water supply systems very expensive (Lee *et al.*, 2010; Amin and Han, 2009; Helmreich and Horn, 2009). Harvested rainwater provides water right near the household, reducing the burden of walking long distances to collect water (Mwenge Kahinda *et al.*, 2008). Finding solutions to water-related problems is an accelerator to economic growth and poverty reduction in developing countries (McGarvey *et al.*, 2008; United Nations, 2006). Thus, utilising harvesting rain water has the potential to serve as a solution to increased water scarcity crisis in the developing world (Hatibu *et al.*, 2006; Hartung, 2007; Ghisi and Ferreira, 2007; Amin and Han, 2009; Helmreich and Horn, 2009).

1.4.1 *Harvesting rainwater (collection) in Uganda*

Lye (2009) described rain-water collection systems as those systems using surface/ground catchment areas and those using above-ground rooftop catchment areas. In Uganda, harvesting rainwater is practiced both in rural and urban areas (Howard *et al.*, 2002). Rain water is harvested from a number of surfaces including house roofs of galvanised iron sheets, asbestos sheet, tiles, grass thatched, trees, courtyards, threshing areas, paved walking areas, plastic sheeting and large rock surfaces as shown in pictures below.

Figure 1.4: Concrete tank collecting water from an iron sheet surface (source: http://assets.knowledge.allianz.com/img/rainwater_uganda_47990.jpg)

Figure 1.5: Brick layed tank collecting water from an iron sheet surface (Source: http://www.ugandaruralfund.org/2013/06/29/engineering-students-bring-clean-water-to-poor-households-in-rural-uganda/)

Harvesting rainwater provides drinking water for humans and livestock without moving long distances (Thomas and Martinson, 2007). In addition, it provides water for irrigation and for refilling aquifers in a process called groundwater recharge, water for flushing toilets and clothes laundering (Lye, 2002). Three categories of HRW have been described according to catchment as in-situ rain water harvest, external-field rain water harvest and domestic rain water harvest (Mwenge Kahinda *et al.*, 2007; Helmreich and Horn, 2009). In situ HRW is where water is collected on the surface where it falls and stored on-site whereas external-field rain water harvest is where rainfall runoff is collected on a surface originating elsewhere and stored off-site. Both in-situ and external-field rain water harvesting are used for agricultural purposes. Domestic rain water harvesting is where water is collected from roofs, street and courtyard runoffs (Mwenge Kahinda *et al.*, 2007; Helmreich and Horn, 2009) and was the focus of this study.

The total storage volume (size) of a tank for a household is recommemned to be calculated as the volume of water required by a household per day multiplied by the number of days in the longest dry season (Parker *et al.*, 2013). In Uganda, this is rarely done due to lack of sufficient funds to buy the required volume. Many people in Uganda use tanks of different sizes ranging from 20L jerry cans to thousands of liters either by custom (what is being used by everyone else) or according to what one can afford (Parker *et al*., 2013) since the bigger the size the higher the cost.

HRW in metallic container of 100L (imported with chemical)

HRW in a clay pot of about 10L

HRW in plastic containers of about 20L

HRW in a plastic jerry can of 20L

Figure 1.6: Harvesting Rainwater in used containers. Source: Google search

The collection/storage vessels can include 5-20-L jerry cans, 50 and 100L blow moulded or plastic drums; 200L steel drums; 420 to 1,500L cement jars; plastic tanks (Aquatank and Polytank) of 220 L to 15,000 L; above-ground plastic-lined tanks (3,000L); below ground plastic-lined tanks (10,000L and above); ferro-cement-concrete tanks (4,000 to 10,000 L); partially below ground cement-concrete lined tanks (6,000 to 10,000 L) and brick tanks (10,000 L) (Danert and Motts, 2009). These containers are described as manufactured/portable (plastic bowls and buckets, jerry cans, clay or ceramic jars, cement jars, old oil drums, empty food containers, etc) or as built-in-place (for example concrete cisterns) (Danert and Motts, 2009).

Large tanks are usually used by institutions for large rain water collection projects but not by households in rural areas as they are expensive to install. Tanks and cisterns are normally used by these large projects because of the many advantages they offer. Tanks being above ground structures, are easy to inspect for leakages, can also be made in several designs using a wide variety of materials, are easy to construct from traditional materials, water extraction can be by gravity in many cases and can be raised above ground level to increase water pressure. However, tanks have also demonstrated some disadvantages for example, requiring large space, being generally more expensive, more easily damaged and also are prone to attack from weather.

Cisterns (underground tanks) are known to be generally cheaper due to lower material requirements, from which they are made, not easy to lose water by leaving a tap on accidentally, save space by being underground, and also the surrounding ground gives support allowing lower wall thickness and thus lower costs. On the other hand, water extraction is more problematic often requiring a pump, leaks are more difficult to detect, contamination of the cistern from groundwater is more common, tree roots can damage the structure, there are the dangers of drowning for children and small animals if the cistern is left un covered, and heavy vehicles driving over a cistern can cause damage.

The choice of system however depends on a number of technical and economic considerations for example space availability, options available locally, local traditions for water storage, cost (purchasing new tank, materials and labour for construction), materials and skills available locally, ground conditions and style of HRW (whether the system will provide total or partial water supply).

A number of factors that influence the HRW system used include rainfall quantity, rainfall pattern, as well as the total rainfall, A climate where rain falls regularly throughout the year will mean that the storage requirement is low and hence the system cost will be correspondingly low and vice versa. Other factors, for example collection surface area (m^2), available storage capacity (m^3), daily consumption rate (liters/capita/day), alternative water sources and cost are also reported to be among the major factors that influence HRW schemes (Baguma *et al.*, 2010b).

There has been an increase in the use of iron sheets in rural areas from 52% in 2000 to 60% by the year 2006 (UBOS, 2006b). A survey of 50 households in the two rural districts of Nakasongora and Tororo revealed that the average area of roofs was 5m^2 per inhabitant with 66% of the 50 households having roof sizes of above 3 m^2 per inhabitant (Thomas and Kiggundu (2004). The uptake of HRW technology is predicted to continue growing tremendously in Uganda (Danert and Motts, 2009) since the percentage of galvanised iron roofs is increasing in addition to increased home ownership in rural areas. The increased use of HRW technology in rural areas is further supported by increased awareness prompted by Government, NGOs and other institutions.

Moreover, HRW has been reported to vary depending on a number of factors which include local weather conditions, for example wind speed and direction (Evans *et al.*, 2006), catchment nature (nature of collecting surface) (Helmreich and Horn, 2009), season (Martin *et al.*, 2010), size of storage device and its design, which influence the water abstraction (handling practices) (Lye, 2009; Simmons *et al.*, 2001; Chang *et al.*, 2004; Zhu *et al.*, 2004; Magyar *et al.*, 2007; Hey-worth *et al.*, 2006).

1.4.2 *Quality of harvested rainwater*

Harvesting rainwater has been used on a small scale and mainly for non- potable purposes; however, due to increased scarcity of water resources as a result of climate change, its use for potable purposes is increasingly becoming adopted (Amin and Han, 2009; Baguma *et al.*, 2010b; Mwenge Kahinda *et al.*, 2010). In fact in Uganda, HRW is widely practiced in most rural areas (Baguma *et al.* 2010a) and is supported by both government and donors promoting the practice (Baguma *et al.*, 2010b).

Despite the fact that HRW is seen as an alternative source of potable water (Hatibu *et al.*, 2006; Hartung, 2007; Ghisi and Ferreira, 2007), many recent studies have questioned its microbial and chemical water quality (Simmons *et al.*, 2001; Chang *et al.*, 2004; Zhu *et al.*, 2004; Sazakli *et al.*, 2007; Lye, 2009; Lee *et al.*, 2010). Rural households have a common consumer perspective that convenient access to a large quantity of water for multi-purpose use is of a higher priority than the quality of that water for human consumption purposes (Danert and Motts, 2009). Part of the consequences of this perspective is rural areas facing severe water shortage problems as well as increased risks of water borne disease as a result of different initiatives concentrating more on water supply and not safe water supply (Baguma *et al.*, 2010)

One of the major strategies to achieve the goal of halving the amount of people with no ccess to safe drinking water by year 2015 (United nations, 2007) is promoting household water treatment and safe storage systems (HWTS). However, this has not yet been adequately addressed in Ugandan rural communities (Baguma et al., 2010). Many of the villages in Uganda where government projects have supported installation of HRW tanks were still lacking knowledge regarding water management and hygienic practices for safe water delivery (Baguma *et al.*, 2010).

1.4.2.1 Chemical water quality of harvested rainwater

Worldwide, several studies have been carried out to evaluate the chemical composition of HRW (Good, 1993; Forster, 1996, 1998, 1999, Uba and Aghogho, 2000; Zobrist *et al.*, 2000; Gromaire *et al.*, 2001; Simmons *et al.*, 2001; Polkowska *et al.*, 2002; Van Metre and Mahler, 2003; Chang *et al.*, 2004; Adeniyi and Olabanji, 2005; Kim *et al.*, 2005a,b; Spinks *et al.*, 2006; Berndtsson *et al.*, 2006; Melidis *et al.*, 2007; Magyar *et al.*, 2007; Peters *et al.*, 2008).

Good (1993) reported all samples tested in his study on sawmill rooftops along the coast of Washington State in the USA, to have exceeded the ambient water quality (US EPA, 1986) guidelines for copper, lead and zinc. Forster (1996, 1998, and 1999) also revealed high levels of heavy metals, however, their concentrations varied with a number of factors summarized in Table 1.3. Simmons *et al.* (2001) investigated one-hundred and twenty-five domestic rooftop rain water systems in four rural Auckland districts for levels of heavy metals (zinc, copper and lead). The study found 14% of the systems exceeding New Zealand levels for lead in drinking water, 2% for copper levels and 1% exceeding zinc guidelines. Runoff pollution was found to contribute 80% of the cadmium, lead and zinc contamination during wet weather flow in the combined sewer system for the entire study area in Paris, France (Gromaire *et al.*, 2001).

Rooftop runoffs from the buildings at Camp Mabry-Texas-USA contributed 55% of specific heavy metal concentrations measured in the total watershed loads (Van Metre and Mahler, 2003). Aluminium, magnese, copper, lead, and zinc exceeded US EPA fresh water quality standards (1999) in a large percentage of samples (Chang *et al.*, 2004) as summarized in Table 1.3 below. Berndtsson *et al.*, (2006) also reported high chemical concentrations in runoff from monitored vegetated rooftops in the four different regions of Sweden for metals and other nutrients. Many studies have reported high levels of chemical composition in roof runoff which are above the recommended standards for fresh water/ drinking water and a few studies have indicated roof run offs with chemical composition adhering to the study country's guidelines (standards). For example, most of the physico-chemical qualities of rainwater (except for color) in Nigeria were within the acceptable guidelines for potable water according to the WHO (1993). However, the runoff from most rooftops wouldn't meet potable water quality without any treatment such as boiling, chlorine tablets and solar water disinfection (Adeniyi and Olabanji, 2005; Uba and Aghogho, 2000).

Table 1.3: The percentage of samples that exceeded the US EPA Freshwater quality standards (1999) for the different rooftop types (Source: Chang *et al.*, 2004)

Water chemical ion	**US EPA Recommend levels (mg/l)**	**Roof Type**				**RW only**
		Wood shingle	**Comp. shingle**	**Painted Aluminium**	**Galv. iron**	
Al^{3+}	≤ 0.2	13.6	17.7	12.3	15.9	8.0
Mn^{2+}	≤ 0.05	27.7	14.7	4.9	6.4	8.0
Cu^{2+}	≤ 1.0	76.2	59.6	77.9	77.7	72.0
Pb^{2+}	≤ 0.015	15.1	10.8	12.8	20.3	8.0
Zn^{2+}	≤ 5	99.5	99.5	100.0	100.0	68.0

Galv.-Galvanised, Comp.-composite, RW-Rainwater.
Note: Wood shingle-Thin tapered pieces of wood of different trees forexample heartwood of large old cedar trees treated with chemicals to avoid rodents and fires; composite shingle-Roofs made from materials of fiberglass mats coated with asphalt and granules.

1.4.2.2 Microbial water quality of harvested hainwater

Although HRW improves water supply, water-related risks and diseases still occur which reduce the expected health improvement achievements (Efe, 2006; Chang *et al.*, 2004; Pinfold *et al.*, 1993).

Potable water scarcity is one of the major issues facing the world today especially in the developing world (Lye, 2009; Palmateer *et al.*, 1999, Meierhofer and Landolt, 2009). Even in those parts of the world that appear to have adequate water supplies, there is a constant need for safe water provision to balance existing supplies with ever growing demands (Lye, 2009). The imbalances in supply of safe drinking water has led to high risks for waterborne diseases such as cholera, typhoid fever, hepatitis A, amoebic and bacillary dysentery as well as many other diarrhoeal diseases (Meierhofer and Landolt, 2009). Every year, millions of people mostly in the developing world are reported to die from diarrhoea and 90% of these are children of under 5 years (WHO/UNICEF, 2009, 2011; Meierhofer and Landolt, 2009). Water demand has also been reported to have increased in over the last half-century with signs of water shortage increasingly manifest as in Switzerland (Matondo *et al.*, 2005) and Aegean archipelago islands (Kaldellis and Kondili, 2007). Today, Uganda is experiencing increased number of drought days and increased levels of rain fall within a short period of time causing floods as a result of climatic change.

Despite the fact that HRW is one intervention being promoted by the Ugandan Government, NGOs and CBOs to increase access to safe drinking water, little is known on its microbiological quality in Uganda. Water quality of HRW both in terms of chemical and biological composition has been repeatedly reported to vary from place to place (Evans *et al.*, 2006; Lye, 2009; Nakata *et al.*, 1995; Nair *et al.*, 2001 a,b) and on many occasions not meeting the requirements for safe drinking water before treatment (Lee *et al.*, 2010; Good, 1993; Forster, 1996, 1998, 1999; Simmons *et al.*, 2001; Van Metre and Mahler, 2003; Levesque *et al.*, 2008).

Unlike in other parts of the world, in Uganda little or no work has been done to evaluate the microbiological qualities of HRW. In this regard, in spite of the many advantages of HRW as an alternative, the use of rain water for potable purposes in Uganda is still not common. This is mainly due to lack of knowledge both within the general public and within local governing agencies concerning microbial quality of HRW. Water intended for human consumption (drinking/ potable purposes) requires much more stringent guidelines for allowable levels of contamination and a strong data base needs to be developed.

In spite of the local household's perception that HRW is safe (Danert and Motts, 2009), studies have revealed that HRW can be contaminated and unsafe for drinking without treatment (Amin and Han, 2009; Helmreich and Horn, 2009; Horak *et al.*, 2010; Lee *et al.*, 2010; Zhu *et al.*, 2004, simmons *et al.*, 2001) and thus requires treatment before human consumption (Amin and Han, 2009; Helmreich and Horn, 2009; Lye, 2009). However, the levels of chemical and microbial contamination vary depending on a number of factors which include local environment conditions and weather patterns, for example, wind speed and direction (Vasquez *et al.*, 2003; Evans *et al.*, 2006; Sazakli *et al.*, 2007), cleanliness and age of catchment / collecting surface (Nakata *et al.*, 1995; Nair *et al.*, 2001 a,b), storage tanks, pipes and gutters (Simmons *et al.*, 2001; Chang *et al.*, 2004 and Zhu *et al.*, 2004), season (Forster, 1996,1998,1999; Martin *et al.*, 2010; Lee *et al.*, 2010), size of storage device and its design, and handling practices after water collection. The chemical composition of HRW has been more extensively studied than the microbial composition. (Good, 1993;Thomas and Greene, 1993; Foster, 1996; Good, 1993; Forster, 1996, 1998, 1999, Uba and Aghogho, 2000; Zobrist *et al.*, 2000; Gromaire *et al.*, 2001; Simmons *et al.*, 2001; Polkowska *et al.*, 2002; Van Metre and Mahler, 2003; Chang *et al.*, 2004; Adeniyi and Olabanji, 2005; Kim *et al.*, 2005a,b; Spinks *et al.*, 2006; Berndtsson *et al.*, 2006; Hart and White, 2006; Melidis *et al.*, 2007; Magyar *et al.*, 2007; Peters *et al.*, 2008) The factors that have been reported to influence the microbial quality of HRW are summarized in Table 1.4.

Dirty and poorly maintained roof tops can be contaminated with dust, organic matter, bird and animal droppings and also pollutants from human activities (Nakata *et al.*, 1995; Nair *et al.*, 2001 a,b; Simmons *et al.*, 2001). These can lead to microbial contamination of collected rainwater with different organisms ranging from bacteria, viruses and protozoa (Evans *et al.*, 2006; Sazakli *et al.*, 2007) as well as chemical changes (Lee *et al.*, 2010). A variety of microbes both biological indicators and potential human pathogens in varying counts up to thousands CFU/100mL have been recorded in HRW (Zhu *et al.*, 2004; Sazakli *et al.*, 2007). Studies have also reported *Escherichia coli* and *Enterococci* (Sazakli *et al.*, 2007), *Aeromonas* spp., *Salmonella* spp., and *Cryptosporidium* spp. (Simmons *et al.*, 2001) in HRW.

Table 1.4: Factors that influence the microbial quality of rooftop harvested rainwater

Factor	Description	Reference
Local climate and weather patterns	Antecedent of dry season, wind speed and direction	Vazquez *et al.*, 2003; Evans *et al.*, 2006; Sazakli *et al.*, 2007
Season	Rain or dry season	Forster, 1996; Martin *et al.*, 2010; Lee *et al.*, 2010; Evans *et al.*, 2006;
Precipitation event	Intensity, wind and duration	Forster, 1996
Nature of catchment	Size, inclination and exposure	Nakata *et al.*, 1995; Nair *et al.*, 2001 a,b
Quality of the atmosphere	Can be polluted with different micro-organisms	Helmreich and Horn, 2009
Collecting surface/roof material	Type, cleanliness (maintenance), age, chemical characteristics, roughness, surface coating	Forster, 1996; Lye, 2002; Albrechtsen, 2002
Nature of storage tanks, pipes and gutters	Design and size of storage device which influence water handling for example water abstraction	Simmons *et al.*, 2001; Chang *et al.*, 2004 and Zhu *et al.*, 2004, Magyar *et al.*, 2007; Hey-worth *et al.*, 2006

A number of studies have reported disease outbreaks associated with consumption of untreated HRW worldwide (Hey-worth, 2006; Ashbolt and Kirk, 2006; Simmons *et al.*, 2008; Franklin *et al.*, 2009). In 2006 an outbreak of *Salmonella mississippi* was reported on Australia's island state of Tasmania (Ashbolt and Kirk, 2006) and in 2008, an outbreak of Legionnaires disease in an isolated suburb of Auckland, New Zeland was also reported (Simmons *et al.*, 2008). Another outbreak in rural Victoria, Australia was reported in 2009 (Franklin *et al.*, 2009) and all these outbreaks were associated with drinking untreated HRW.

Simmons *et al.* (2001) investigated one-hundred and twenty five domestic rooftop rainwater systems in four rural Auckland districts for microbial contamination. Their study suggested that rooftop rainwater was of relatively poor quality. Potential microbial pathogens such as *Salmonella, Aeromonas and Cryptosporidium* were identified in some of the rooftop collected rainwater. In fact, their survey suggested a significant association between the presence of *Aeromonas* and increased gastro-enteric symptoms among household users.

In a review by Lye (2002) on the common occurrence of various pathogenic microorganisms reported in rainwater systems worldwide, it was concluded that consuming untreated rainwater from rooftop collection could be contributing to a number of diseases, ranging from bacterial diarrhoea and bacterial pneumonia, to tissue helminth infestations.

In 2007, a study by Sazakli *et al.*, (2007) revealed coliforms in 80.3% of rain water samples while 40.9% and 28.8% had *Escherichia coli* and Enterococci, respectively. In the same year, a study carried out by Fewtrell and Kay (2007) identified a number of pathogens in stored HRW with *Salmonella* spp being the most common as summarized in Table 1.5 below.

Levesque *et al.*, (2008) reported a high frequency of faecal contamination in household tank rain water collected during a study of 102 households in Bermuda and this was attributed to ineffective preventive measures to water contamination in houschold.

Table 1.5: Some of the pathogens common in rainwater supplies in developed countries, for example, Australia, USA, Denmark (adapted from Fewtrell and Kay, 2007)

Pathogen	Infection	Transmission	Case fatality rate per 100,000 cases
Campylobacter spp.	Gastroenteritis	Oral	5
Escherichia coli (O157:H7)	Gastroenteritis	Oral	8.3
Pneumophila spp.	Pontiac fever	Inhalation	Zero
Mycobacterium avium	Respiratory	Inhalation	only in immune-compromised individuals
Salmonella spp.	Gastroenteritis	Oral	41
Cryptosporidium spp.	Gastroenteritis	Oral	22
Giardia spp.	Gastroenteritis	Oral	1

1.4.3 *Disease outbreaks in relation to consumption of untreated HRW*

Several disease outbreaks have been reported to be associated with rainwater consumption. Between 1978 and 2006, three outbreaks (two involving bacterial gastroenteritis and one involving bacterial pneumonia) were registered (Hey-worth *et al.*, 2006).

In 2008, Simmons *et al.* reported an outbreak of Legionnaires disease in an isolated suburb of Auckland, New Zeland (Simmons *et al.*, 2008). Using molecular-based technology they showed that the isolates of *Legionella pneumophila* from patient clinical specimens were identical to the high levels of *L. pneumophila* present in the nozzle of a local marina water blaster used to clean boats. Sampling of nearby rainwater collection systems revealed that contaminated water spray from the water blaster had been carried and deposited on roof surfaces in the local area. The *L. pneumophila* within the spray were washed into rainwater storage tanks and users were exposed through bathroom showers.

An outbreak of gastroenteritis associated with consumption of contaminated rainwater was reported at a rural school camp in Victoria, Australia by Franklin *et al.* (2009). Their report associated the outbreak with rainwater collection tanks which were contaminated with *Salmonella typhimurium* definitive phage type 9 (DT9). The same phage type strain (DT9) of *Salmonella* was found in both the faecal specimens of patients and water taps supplying harvested rain drinking water.

In a study carried out by Ahmed *et al.* (2008) on microbiological quality of roof-harvested rainwater from tanks in Southeast Queensland, Australia using *E. coli*, enterococci, *Clostridium perfringens*, and *Bacteroides* spp., of the 27 rainwater samples tested, 17 (63%), 21 (78%), 13 (48%), and 24 (89%) were positive for *E. coli* , enterococci, *C. perfringens*, and *Bacteroides* spp., respectively. In the researchers further analysis for the presence of potential pathogenic microorganisms using real-time PCR (with SYBR Green I dye), of the 27 samples 11 (41%), 7 (26%), 4 (15%), 3 (11%), and 1 (4%) were PCR positive for the *Campylobacter coli* ceuE gene, the *Legionella pneumophila* mip gene, the *Aeromonas hydrophila* lip gene, the *Salmonella* invA gene, and the *Campylobacter jejuni* mapA gene.

In 2010, Ahmed *et al.* carried out a study on 82 tanks in urban Southeast Queensland (SEQ) in Australia where he collected a total of 214 samples and analysed them for the presence and numbers of zoonotic bacterial and protozoal pathogens using binary PCR and quantitative PCR (qPCR). Out of 124 samples, 10.7%, 9.8%, 5.6%, and 0.4% were positive for the *Salmonella invA*, *Giardia lamblia* β-giardin, *Legionella pneumophilamip*, and *Campylobacter jejunimapA* genes, respectively. The estimated numbers of *Salmonella*, *G. lamblia*, and *L. pneumophila* organisms ranged from 6.5×10^1 to 3.8×10^2 cells, 0.6×10^0 to 3.6×10^0 cysts, and 6.0×10^1 to 1.7×10^2 cells per 1,000 ml of water, respectively (Ahmed *et al.*., 2010). Harvesting rainwater has therefore been recommended for treatment before human consumption (Lye, 2009; Simmons *et al.*, 2001). In fact, Baguma *et al.* (2010) strongly recommended a study on microbial quality of HRW in rural areas of Uganda.

Many countries all over the world are therefore developing guidelines for rooftop runoff collection as rainwater harvesting is increasingly dominating water supply to adapt to climatic change (Lye, 2009). In regard to this development, a number of parameters have been indentified and described in order to optimize efficient performance of rain water collection systems (Lye, 2002) as outlined below.

- Proper design/sizing of all parts of the system
- Use of most appropriate materials in construction
- Exposed metal surfaces that contribute heavy metals to the runoff contamination
- Coating of metal surface rooftop materials minimizes leaching
- Deposition of material from local environments is the predominant source of contamination for rooftop runoff
- The type of impervious roofing material used (ceramic tile, clay tile, asphalt) is secondary to the material deposited on roof catchments as a source of contamination
- Proper treatment/disinfection materials and procedures
- Regular schedules of maintenance for existing systems
- Intended use of the water
- Periodic testing of water quality
- Education and certification of individuals associated with the governing, approval, and use of these types of systems

Because of a number of likely contaminants that have been found in HRW, a lot of research is required to evaluate the sustainable affordable, accessible and efficient treatments for rooftop runoff by individual households (Helmreich and Horn, 2009). Jordan *et al.*, (2008) studied the use of filtration and ultraviolet disinfection to deliver high quality drinking harvested rain water and the findings reported success in disinfection of total coliforms, *Escherichia coli* and Enterococci.

1.5 TREATMENT OF HRW

There are many household water treatment methods in Uganda for example, slow sand filtration, boiling, and chlorination ("water guard"). However, they are expensive and thus not easily available to rural communities in Uganda. Despite the fact that a single tablet of water guard that treats 20L of water costs 500Ug shs (0.2US $), many rural households cannot afford them. Some methods like chlorine tablets (water guard-bleach) in addition to cost are not preferred by the rural communities because of the smell (odour). Chlorine use has also been reported to be limited by its reaction with dissolved organic matter which settles to the bottom of the tanks and form undesirable by-products for example trihalomethanes and haloacetic acids which present health risks to consumers (Gordon *et al.*, 1995). Some parasitic species have also shown resistance to low doses of chlorine and this further limits its use to disinfect HRW (Helmreich and Horn, 2009).

Slow sand filtration is another cheap method to improve the bacterial quality of water used by households (Thomas *et al.*, 2004; Jenkins *et al.* 2011; Palmateer *et al.*, 1999). However, the use of slow sand filters is highly limited by the fact that it requires frequent maintenance (Helmreich and Horn, 2009). Recent studies have developed a technology with ceramic membrane for treating HRW with the ability to filter out even the smallest viruses and bacteria (Mohr, 2006, Sobsey *et al.*, 2008)). However, the technology is very expensive and thus not suitable for household treatment but for central treatment of collected rainwater (Helmreich, 1999). Therefore people are still consuming untreated water which exposes them to diarrheal water borne diseases like cholera, especially among children of less than 5 years (Baguma *et al.*, 2010). Water borne diseases due to the consumption of microbiologically contaminated drinking water is thus still among the major causes of diarrheal diseases in Uganda, which are particularly dangerous to children.

1.5.1 *Solar Water Disinfection (SODIS)*

1.5.1.1 History of SODIS

Solar water disinfection is known as a cheap (McGuigan *et al.*, 2012) and accessible treatment technology. The method uses solar energy to disinfect disease causing pathogens. The technology is not recent and has been in existence for almost 2000 years. The technology originated from descriptions of communities in the Indian sub-continent who used to place drinking water outside in open trays to be "blessed" by the sun nearly 2000 years ago (Baker, 1981). Although in 1877 when rigorous investigations were done on the bactericidal effect of sunlight by Downes and Blunt (Downes and Blunt, 1877), it was not until 1984 when the first publications on the seminal work on using sunlight to disinfect contaminated water for use in oral rehydration solutions was done by Aftim Acra and co-workers in the University of Beirut (Acra *et al.*., 1980; Acra *et al.*, 1989). The treatment was termed as SODIS for the first time almost three decades ago (Acra *et al.*, 1984) and from this time, a lot of research has been done to investigate the potential of SODIS to inactivate a wide range of waterborne pathogens (Joyce *et al.*., 1992; Wegelin *et al.*, 1994; Conroy *et al.*, 1996; Sommer *et al.*, 1997; Reed, 1997; McGuigan *et al.*, 1998).

SODIS uses two mechanisms of water treatment; heating or thermal effects resulting in pasteurization and UV-A radiation (optical), which can work independently (Eisenstark *et al.*, 1987; Cooper *et al.*, 1988; Davies and Evison, 1991; Joyce *et al.*, 1996). However, studies have also indicated synergistic effects when thermal and optical mechanisms are applied together at temperatures >45°C (McGuigan *et al.*, 1998). In the first studies, Acra *et al.* (1984) used transparent glass and plastic containers and found solar radiation effective in inactivating a wide range of microorganisms, including faecal indicators. Solar disinfection processes were further investigated for almost a decade later using batch reactors of small volume of 1-2L for disinfection of drinking water (Goswami 1995, 1997; Cooper and Goswami 1998). Other approaches like different blackening surfaces have been also evaluated to enhance the efficiency of SODIS by increasing the thermal effects of reflective polyethylene terephthalate (PET) bottles (Sommer *et al.*, 1997; Kehoe *et al.*, 2001; Amin and Han, 2009). Other enhancement technologies for example, compound parabolic collectors (CPC) with the ability to treat higher volumes of about 25L both by continuous or batch techniques which have also been designed and studied. However, most of these studies have been carried out from either laboratories or in developed countries where the climate (weather) conditions are different from those of developing countries like Uganda.

1.5.1.2 Use of SODIS in households

Solar water disinfection is a simple technology which involves exposing the bottle to sunlight. WHO and UNICEF (2011) highly recommend this technology for household water treatment due to the fact that it's cheaper and easy to apply. As shown in Figure 1.7 below, it involves only four steps (McGuigan *et al.*, 2012).

Figure 1.7. Method of carrying out SODIS (1: filling a PET bottle with water for treatment, 2:exposing the filled PET bottles to sun on a roof top, 3: leaving the PET bottles on sun for 6 hours on sunny days and 2 days on cloudy days, 4: drinking the treated water from the PET bottle).

Several authors have recommended treatment of HRW before consumption (Simmons *et al.*, 2001; Evans *et al.*, 2007; Han and Mun, 2008; Levesque *et al.*, 2008; Helmreich and Horn, 2009; Amin and Han, 2009) and this should be affordable and applicable to local communities in order to be sustainable (Helmreich and Horn, 2009). The authors further state that the technology should be sustainable in terms of the energy required, inexpensive (Helmreich and Horn, 2009) and appropriate for removing microbial hazards and parasites (Palmateer *et al.*, 1999; Amin and Han, 2009).

Solar disinfection has been outlined as one of the sustainable economically viable water treatments suitable for rural communities in developing countries, most of which are known for receiving plentiful high levels of solar radiation (WHO, 2008; Fisher *et al.*, 2008; Helmreich and Horn, 2009, Bosshard *et al.*, 2009; WHO/UNICEF, 2011). The technology uses easily accessible local materials and low cost tools (Bosshard *et al.*, 2009). The method has spread throughout the developing world and is in daily use in more than 50 countries in Asia, Latin America, and Africa. More than 5 million people disinfect their drinking water with this technique (McGuigan *et al.*, 2012). Not only WHO (2008) but subsequent authors have also recommended SODIS as one of potential disinfection techniques suitable for treating harvested rain drinking water (Meera and Ahammed, 2008; Amin and Han, 2009; Amin and Han, 2011). However, the treatment method is still lacking enough scientific and engineering data to support its full adaptation (Amin and Han, 2009). In spite of many studies that have been completed to evaluate the efficiency of SODIS on different sources of contaminated water, for example, waste water (Sinton *et al.*, 2002), fresh water (Dan *et al.*, 1997), sea water (Sinton *et al.*, 1999) and bathing waters (Mascher *et al.*, 2003), the use of SODIS to disinfect HRW for potable purposes in rural areas of developing world has not yet been studied in detail.

In recent years, a number of studies have been carried out in the laboratory on the use of different enhancement methods and technologies to accelerate SODIS disinfection (Smith *et al.*, 2000; Kehoe *et al.*, 2004; Khaengraeng and Reed, 2005; Heaselgrave *et al.*, 2006; Fisher *et al.*, 2008). However, less has been done to evaluate the performance of these different enhancement technologies in the field or in developing world countries such as Uganda. For that reason, there is still a lack of adequate knowledge on solar disinfection application methods and technologies in the developing world like Uganda.

1.5.1.3 Suitability of SODIS in Uganda and the challenges

Solar water disinfection (SODIS) utilizes solar energy which is free and renewable (Helmreich and Horn, 2009; McGuigan*et al.*, 1998; Meierhofer and Wegelin, 2002). Uganda is located at Latitude of 1°00′ North of the Equator and Longitude of 32°00′ East of Greenwich. The most suitable areas for SODIS are those north and south of equator as indicated on Figure 1.8.

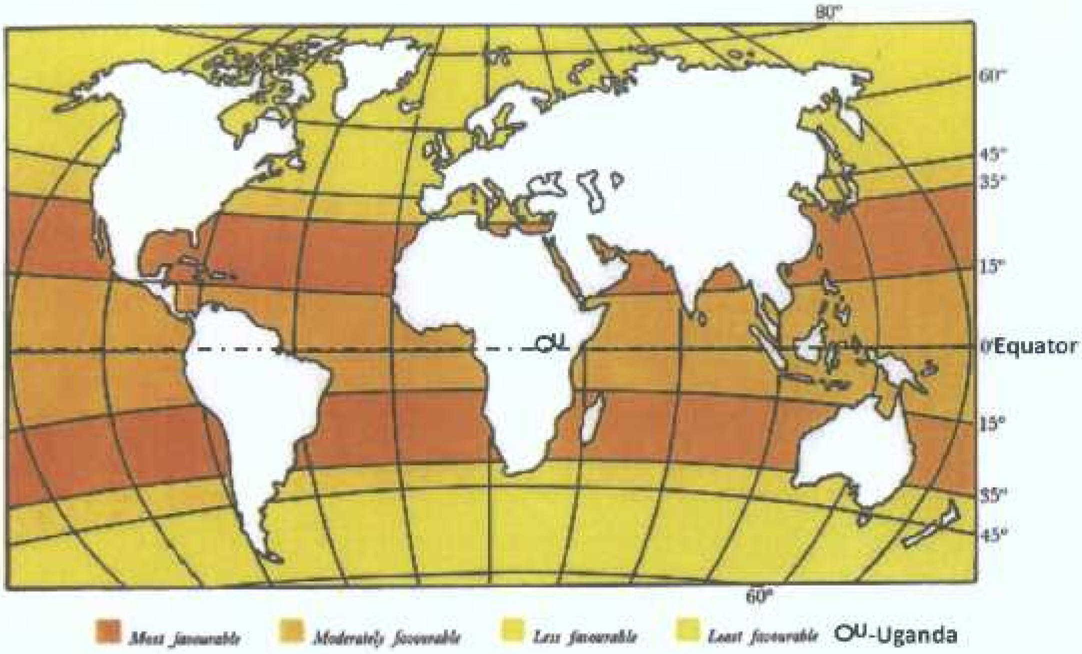


Figure 1.8: Favourable regions for solar disinfection, determined by number of hours and intensity of sunlight (Acra *et al.*, 1984).

Uganda is one of the many countries on the equator (Figure 1.8) moderately favourable for SODIS. The country being on the Equator, it receives high amounts of rainfall corresponding to reduced intensity of sunlight hence making it only moderately favourable for SODIS. On the other hand, the country receives sufficient levels of sunlight throughout the year which are suitable for application of SODIS (Navntoft *et al.*, 2008). The introduction of SODIS is thus a viable sustainable affordable household water treatment worth investing in to improve on safe water accessibility in local areas of Uganda.

Despite the fact that SODIS and HRW technology are suitable in a Ugandan setting, little has been done to evaluate their efficacy in Ugandan rural conditions. A number of limitations have been reported from various studies that have been carried out on different technologies and applications for enhancing SODIS (McGuigan *et al.*, 1998; Khaengraeng and Reed, 2005; Mani *et al.*, 2006; Mendez-Hermida *et al.*, 2007; Fisher *et al.*, 2008; Thiruvenkatachari *et al.*, 2008; Amin and Han, 2009; Amin and Han, 2011). Amin and Han (2009) recommended research on SODIS enhancement technologies to accelerate SODIS processes in order to disinfect HRW for potable purpose. Also, the usual PET bottles that are commonly used for SODIS treat only a maximum of 2L which is not even enough for a person in a day since 3L are recommended to be drunk on daily basis. Therefore, the present study further evaluated the use of a 25L CPC to enhance SODIS water treatment technology. Some studies for example

(Ubomba-Jaswa *et al.*, 2010) have reported no regrowth of bacteria after SODIS treatment, however, the results of Amin and Han (2009) suggest possibilities of *E. coli* re-growth and recommend thorough studies on bacterial re-growth during SODIS studies. Therefore in this study microbial re-growth after SODIS treatments was further investigated.

1.5.1.4 Use of SODIS (2L PET bottles) to disinfect HRW

Much of the research in understanding the mechanism of this process has been done using transparent plastic bottles exposed to sunlight under different operating conditions. Results have shown that 6h of solar exposure is sufficient to inactivate most bacterial pathogens in contaminated water when using polyethylene terephthalate (PET) bottles of up to 2 L in volume (Kehoe *et al.*, 2001; Meierhofer and Wegelin, 2002). Since 1980 when SODIS work was started by Acra *et al* (1980) after reporting that enteric bacteria were inactivated after exposure to 6 h of sunlight, several other organisms have been tested, including: *Salmonella typhimuirum, Shigelladysenteriae, E. coli, Vibrio cholera* and *Pseudomonas aeruginosa* (Berney *et al.*, 2006; Kehoe *et al.*, 2001; McGuigan *et al.*, 1998; Smith *et al.*, 2000), protozoan oocysts of *Cryptosporidium parvum* and cysts of *Giardia muris* (McGuigan, 2006), the yeast *Candida albicans*; the fungus, *Fusariumsolani* (Lonnen *et al.*, 2005) and Polio virus (Heaselgrave *et al.*, 2006). A number of factors that influence the efficiency of SODIS to treat water have been documented and these include physico-chemical parameters like pH, turbidity (Amin and Han, 2009), weather conditions, and the presence of natural organic matter which acts as a photo-sensitizer to improve SODIS efficiency (Curtis *et al.*, 1992). All these factors are likely to be different in HRW depending on catchments. Despite the fact that more than 344,600 people in Africa already use SODIS, for example, DR Congo, Tanzania, Kenya, Zambia, Zimbabwe and Mozambique (Meierhofer and Landolt, 2009), the use of SODIS to treat rain harvested water has not yet been adequately evaluated. Therefore, the current study focused on SODIS and its use to treat HRW.

1.5.1.5 Cost benefit aspects of SODIS

The mean cost of SODIS implementation, including bottles and educational materials, has been documented to total up to USD 0.75 per year per person trained. During the subsequent following years, users pay 0.40 USD on average for SODIS application mainly for replacement of damaged bottles (Meierhofer and Landolt, 2009). The economic benefits derived from improved health as a result of reduced diarrhoea incidences which are manifested in the reduced medical expenses, increased adult productivity and school attendance of children, are much higher than the running costs of SODIS (Meierhofer and Landolt, 2009). Health impact assessments among communities in Pakistan, Uzbekistan, Nepal, Indonesia and India indicate a 50% reduction in diarrhoea rates among more than 970,000 SODIS users. That is 2.4 million diarrhea cases could be prevented annually in the project areas (Meierhofer and Landolt, 2009).

1.6 SODIS ENHANCEMENT TECHNOLOGIES (COMPOUND PARABOLIC COLLECTOR CPC)

When standard SODIS PET bottles are exposed to sunlight, they are only illuminated on the upper side and a large fraction of the available radiation doesn't reach the water. In order to increase the radiation reaching the water, there have been several attempts to concentrate solar radiation using reflecting surfaces.

Martin-Dominguez *et al.* (2005) found that the use of solar concentrators and bottles partially painted black reduced the exposure time required to only 2h to achieve total disinfection of total coliforms and *E. coli*. Although in this enhancement technology a total of 8 L of water was treated by placing 4 bottles of 2L volume each on the rectangular parabolic concentrate in only 2 hours, the challenge with filling up bottles and replacement of PET bottles after 6 months of use remains unsolved. Also, the 8L of water is not enough to satisfy a household of more than 4 people. It is recommended to drink a minimum of 2L of water per day and many households in Uganda have more than 5 people and theirfore require more than 8L of water daily. Therefore, such a CPC would have minimal use in Uganda.

Kehoe *et al.* (2001) found that bacterial decay constants increased two fold by the use of aluminium foil attached to the back of the 1.5L bottles. Although successful results were obtained with reduced exposure time, 1.5L is too small volume for big households and institutions.

Saitoh and El-Ghetany (2002) studied the performance of a wooden hot box solar facility as a solar disinfectant system for treating contaminated water. Although, only three hours were required for treating water to recommended drinking water standards, in addition to large volumes (100L), the enhancement technology is challenging by its cost. Much as the actual cost of construction and maintenance was not stated by the researcher, it seems to be quite expensive to construct it as compared to CPC enhancement technology investigated in the Ubomba-Jaswa *et al.* (2010) study.

McLoughlin *et al.* (2004) investigated on the treatment efficiency of the three reactors, that is compound parabolic, parabolic and V-groove profiles which were constructed using Pyrex tubing and aluminium reflectors (Figure 1.9 below), using *E. coli* K12.

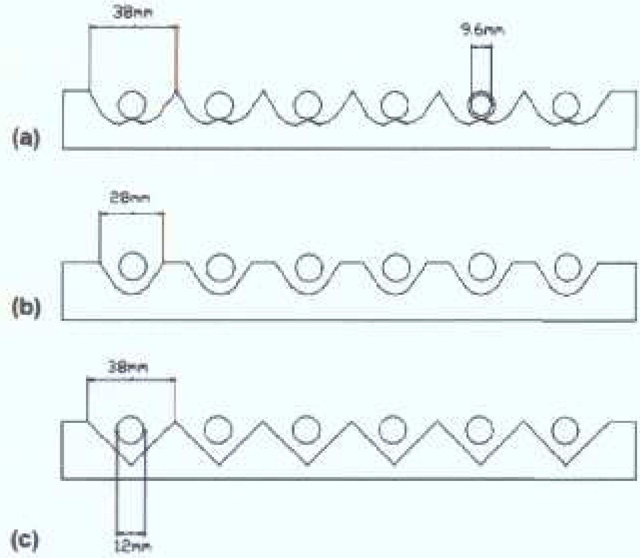


Figure 1.9: Cross section of SODIS enhancement reactors: (a) compound parabolic, (b) parabolic and (c) V-groove (Source: McLoughlin*et. al.* (2004))

Results showed that the compound parabolic reflector promoted a more successful inactivation of *E. coli* than the parabolic and V-groove profiles. Although promising results were obtained with 11L of water in this study, Ubomba-Jaswa *et al.* (2010) experiment showed better results and larger volumes were treated as described below.

Navntoft *et al.* (2008) studied the use of batch reactors to treat *E. coli* in natural well water and successful results were obtained. During sunny (cloudless) days, both controls (bottles without fitted CPC) and CPC fitted bottles successfully inactivated *E. coli* below detection limit of 4 CFU/ml. However, CPC fitted bottles achieved undetectable levels an hour earlier than the controls. Unlike on sunny days, controls did not achieve full inactivation of *E. coli* on cloudy days. It was only the CPC fitted system that achieved full inactivation of *E. coli* with levels below the detection limit on cloudy days. Although the required time of exposure was shortened by an hour in the presence of a CPC, and while successful treatment was achieved on cloudy days with the help of a CPC, the 2.5L volume treated was small and thus a constraint.

Kruti and Shilpa (2012) compared bacterial inactivation in three CPCs with that in PET 1L bottles without a CPC using an *E. coli* suspension under natural solar radiation (cloudy and cloudless) conditions. The results showed a considerably reduced time for complete inactivation of *E. coli* in a CPC compared to PET bottles. On a cloudy day, complete inactivation of bacteria was observed in all three CPCs within 4 hours of exposure whereas in a simple PET bottle, this could not be achieved even after 6 h of exposure. Therefore PET bottles required a second day of exposure for complete inactivation.

Marques *et al.* (2013) investigated the effectiveness of a solar energy concentrator made of cardboard and covered with aluminium foil in heating water in transparent and black-backed PET reactors. They also compared the efficiency of these reactors with those that are used on asbestos roofing. The black-backed PET reactors in the solar concentrator were found to be better at heating water than any of the other treatments, both on strong and moderate sunshine days. On weak sunshine days, however, these reactors did not heat the water enough for solar disinfection to take place. The river water samples exposed to 3 h of solar radiation on moderate weather days had 99.9% inactivation of faecal coliforms (*E. coli*) when the water reached more than 50°C (average 6 h peaks of radiation –685.6 W/m^2). However, inactivation of faecal coliforms was not observed in reactors exposed to solar radiation in the same weather conditions on asbestos roofing. Although this innovation resulted in the inactivation of bacteria after shorter periods of exposure, the 2L volume that was treated made the innovation less suitable for large households and institutions as compared to that of Ubomba-Jaswa *et al.* (2010).

Ubomba-Jaswa *et al.* (2010) investigated the microbial inactivation efficiency of a 25L batch solar disinfection (SODIS) reactor enhanced with a compound parabolic collector (CPC) for household use with *E. coli* K-12. During periods of strong sunlight, complete inactivation of bacteria occurred in under 6h. Under cloudy and low solar intensity conditions, prolonged exposure was needed. Turbid water (100 NTU) was disinfected in 7 h with water temperatures >50°C. The results showed no regrowth of bacteria in this study.

Although a big volume of water (100L) is treated by the enhancement technology used by Saitoh and El-Ghetany (2002), it is very constrained by the high construction and maintenance cost required as compared to the 25L CPC used by Ubomba-Jaswa *et al.* (2010). Ubomba-Jaswa*et al.* (2010) states clearly that the 25L CPC technology used in his study requires very minimal maintenance costs. It's relatively cheaper to construct and maintain the 25L CPC of Ubomba-Jaswa *et al.* (2010). The CPC is reported to cost only 200 US dollars and can be used for more than 2 years without any maintaince costs incurred. However, a laboratory strain was used in this study to test the efficiency of the technology and laboratory strains are known for being more sensitive to treatment than environmental strains (Quek and Hu, 2008). Therefore the reported exposure time could have been somehow underestimated. Therefore, in the current study the same CPC that was used in Ubomba-Jaswa *et al.* (2010) was examined with a wild strain of *E. coli* isolated from polluted natural protected well water to test its efficiency under tropical conditions. Despite the fact that a number of researchers have documented the use of different SODIS enhancement technologies and applications on treatment of drinking water to reduce the solar exposure time in addition to increased treatable water volumes, less has been done on use of enhancement SODIS technologies to treat drinking water at the point of use in Uganda.

Since Ubomba-Jaswa *et al.* (2010) examined the CPC under Spanish environmental conditions which are different from those of tropical countries, the current study examined this same CPC under Ugandan conditions which are typically tropical.

1.7 PURPOSE OF THIS STUDY

This study was part of a large multi-disciplinary project entitled 'Water Is Life: AmazziBulamu' comprising a partnership of Irish Higher Education Institutions (NUI Maynooth, Dublin City University, Trinity College Dublin, The Royal College of Surgeons in Ireland, University College Dublin and Queen's University Belfast), Makerere University, Kampala, Uganda, the Medical Missionaries of Mary and various NGOs.The goal of the partnership, in support of the Government of Ireland's development goals, was to build research capacity in Ireland and Africa and to conduct research that supports sustainable water resource management as a catalyst for sustainable economic and social development in rural Uganda (www.waterislife.ie).

The project was carried out in Makondo-Lwengo, Masakaa a rural area south of the Equator where one of the partners, the Medical Missionaries of Mary, was already established and working with the rural community. They identified the need for research on the local water supply and this led to the development of this project together with seven other projects. Four of the projects focused on technology while the other four investigated social issues. The other seven projects studied;

- The efficacy of SODIS in rural primary schools in Uganda
- The functional sustainability of diamond-like carbon (DLC) and silicon doped diamond-like carbon (Si-DLC) coated nitrile rubber piston seals for hand pumps
- Sourcing sustainable groundwater for rural water supplies: An assessment of a weathered crystalline rock aquifer system in Central Uganda
- Women as principal gate keepers: an ethnographic research study on, water and health in rural Uganda
- Enabling Community-Based Water Management Systems: Governance and Sustainability of Rural Point-water Facilities in Uganda
- Gender, Power and Local Water Governance in Rural Uganda
- A dynamic assessment of adaptive capacity to climate change: A case study of water management in Makondo, Uganda

The Medical Missionaries of Mary (MMMs) had been working in the area for more than 20 years and this enabled the researchers to gain access to the local community. The researchers were also able to build on the work already done by the MMMs in the area. This included the provision of education for children, medical care in particular to HIV patients, nutritional trainings to mothers and the provision of houses to windows, orphans and older people. When houses were supplied, harvested rainwater tanks were also provided. The main objective in providing the tanks was to ensure a supply of water to the most vulnerable people in the area. This water was used for drinking however the quality of the water had never been examined.

A visit to the community enabled an inspection of the HRW tanks, how they were managed and how the water was stored. It was clear that the microbial quality of the HRW was questionable. On interviewing the households on the household water treatment methods used, many mentioned the absence of any treatment due to the lack of the required resources such as firewood for boiling. The majority of those interviewed indicated a dislike to the use of chlorine tablets because of the associated smell. The use of solar water disinfection (SODIS) was therefore considered as an effective, economic and user friendly technique.

1.8 AIMS AND OBJECTIVES

The aims of the project were to investigate the quality of HRW in the rural area of Mokondo and to determine the effectiveness of SODIS to treat the raw water. The objectives were to;

1. Carry out a preliminary study to determine the quality of the HRW and the use of SODIS
2. Study the physicochemical and microbiological quality of the HRW over a 12 month period and to assess the microbial quality of HRW over different Ugandan seasons in a year
3. Assess the effectiveness of using SODIS with 2L PET bottles for treating HRW under field conditions of Uganda.
4. Evaluate a 25L borosilicate glass batch solar disinfection reactor fitted with a compound parabolic collector under Sub-Saharan field conditions

2 METHODOLOGY

2.1 LOCATION OF THE STUDY

The study was carried out in the Makondo sub-parish which is located west of the Masaka District (newly named Lwengo District) in Uganda. The district is located South-East of Uganda along the border with Lake Victoria (Figure 2.1(a and b)). It lies at over 1,100 meters above sea level between the latitude of 0 degree 29.67 minutes South and longitude of 31 degrees 28.663 minutes East.

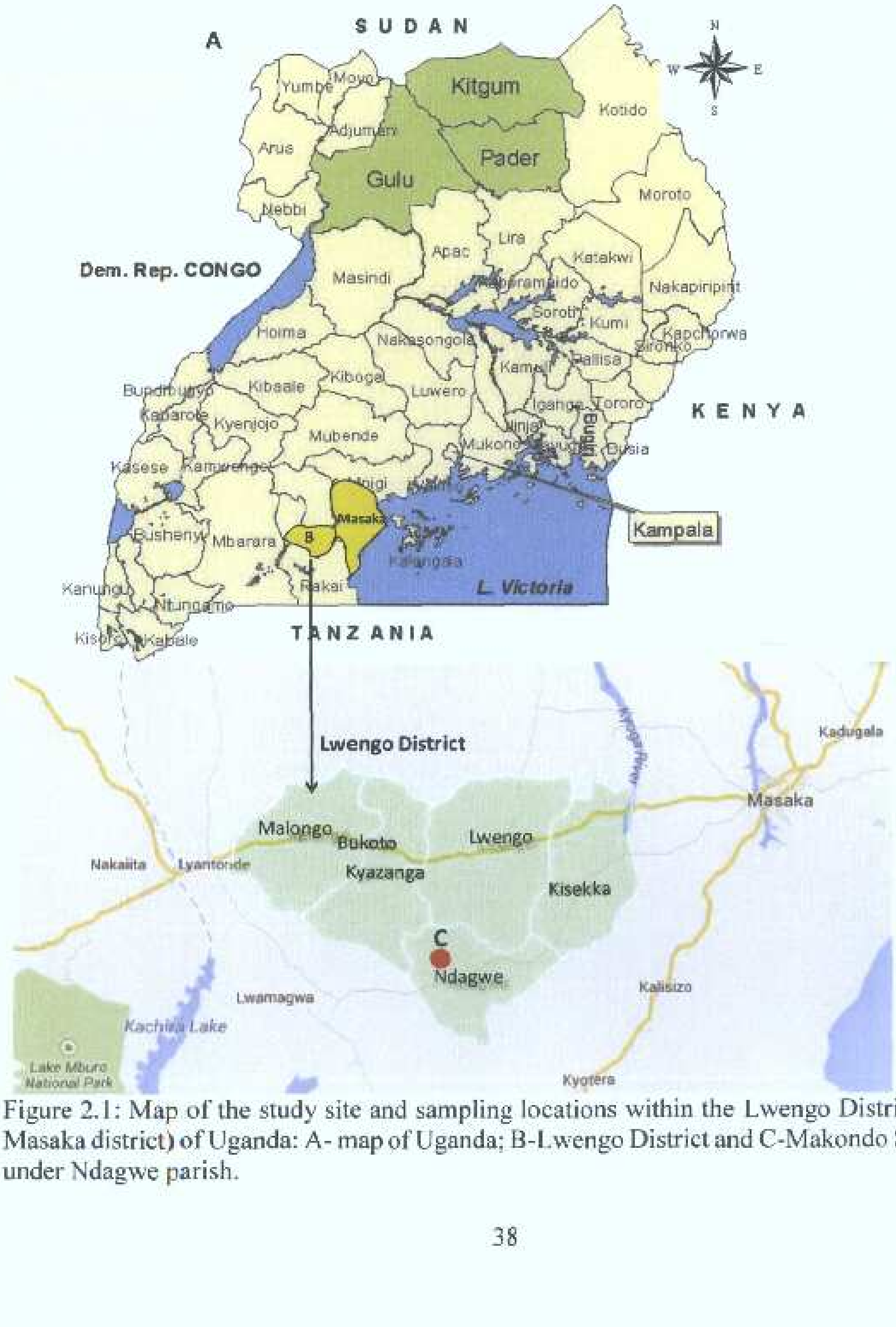


Figure 2.1: Map of the study site and sampling locations within the Lwengo District (former Masaka district) of Uganda: A- map of Uganda; B-Lwengo District and C-Makondo Sub-parish under Ndagwe parish.

2.2 THE STUDY FLOW DIAGRAM

An outline of the study is described in Figure 2.2. Ethical approval for the study was first obtained. Households were selected and trained in SODIS disinfection before commencement of the study. A preliminary study was carried out for four months to establish the quality of the HRW and this was followed by a twelve month study. The measurement of physicochemical parameters was carried out in the field whereas the microbiological examination of the water was carried out at the Department of Food Technology and Nutrition, Makerere University. A second study was conducted in the urban setting of Kampala to test the efficacy of a 25L compound parabolic reactor to treat contaminated water.

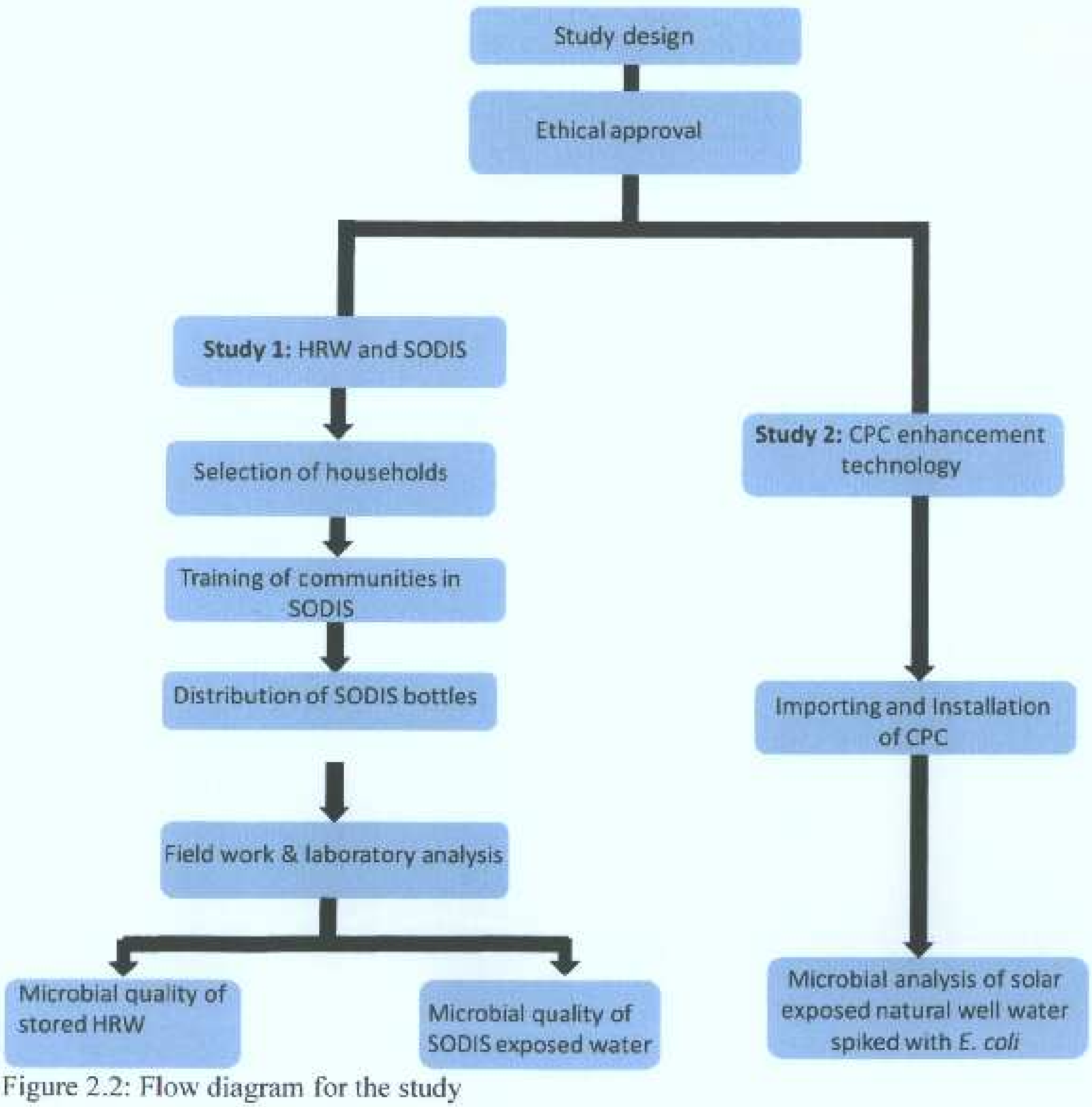


Figure 2.2: Flow diagram for the study

2.3 ETHICAL APPROVAL

Ethical approval was sought from the Research Ethics Committee (REC) of the Royal College of Surgeons in Ireland. Approval was needed to ensure appropriate study design so that there would be no negative impacts on the community. The researcher was required to thoroughly explain the purposes of the research, risks and benefits associated with the research and the fact that subjects could decide to drop out of the study at anytime without any consequences whatsoever to them. Approval was granted in December 2010 after which field work began. Copies of research ethical approval and the consent forms is attached as appendices (1 and 2). Research clearance was also sought from the Uganda National Council of Science and Technology. This is the body approved by the Ugandan Government to coordinate and approve all research based in Uganda.

2.4 SELECTION OF HOUSEHOLDS

The study was started by visiting local leaders Local councils level 1 (LC 1) chair persons in the area to discuss the intentions of the research before selecting households. The chair persons were requested to list all the households carrying out HRW. A local facilitator was employed to help me during the introduction of the study to the locals. LC1 lists drawn were used to visit each of the households with HRW system. Each household was briefed about the study and asked if they were willing to participate in the research. Characteristics of each of the systems were noted, for example, size of the HRW system, material of HRW, the duration a household would use HRW during a dry season and accessibility. A random number of 30 households of those who showed interest were included in the preliminary study based on the size and nature of the HRW system. Those randomly selected households were invited to a meeting together with local leaders from which the purpose of the study was again explained and they were requested to register their names, contacts, and sign commitment to the study as detailed in Appendix 3: Participant information sheet. After the first two months of the study on microbial quality, an interview using a questionnaire with each of the 30 households was held as shown in Appendix 4: Questionnaire Designed to Check the Awareness Level Regarding the SODIS (Solar Water Disinfection) Technique.

After the prelimnary study, fifty households (50 HRW systems) were involved in the main study of which 11 had concrete tanks, 10 metallic tanks of 2000L and above, 10 metallic tanks of below 2000L, 11 plastic tanks and 8 catchment ponds.

2.5 TYPES OF HRW SYSTEMS

Four different types of system were studied – concrete tanks, metallic tanks, plastic tanks and catchment ponds as illustrated in Figure 2.3, Figure 2.4, Figure 2.5 and Figure 2.6.

Concrete tanks: These systems are made from sand, cement and bricks. They were either below the ground or above the ground. Those below the ground were usually larger, above 10,000L than those concrete tanks built above the ground. During the dry season, these were left with some water to avoid breakage hence not left dry at any time throughout the year. Some were cleaned by flushing through some little water when expecting rains within few hours. Others were not flushed at all throughout the year.

Figure 2.3: Concrete tank

Metallic tanks: Metallic tanks are made from iron sheets and varied greatly in size and cost. The majority of these tanks were of 500L and too small to take a household through the entire dry season.

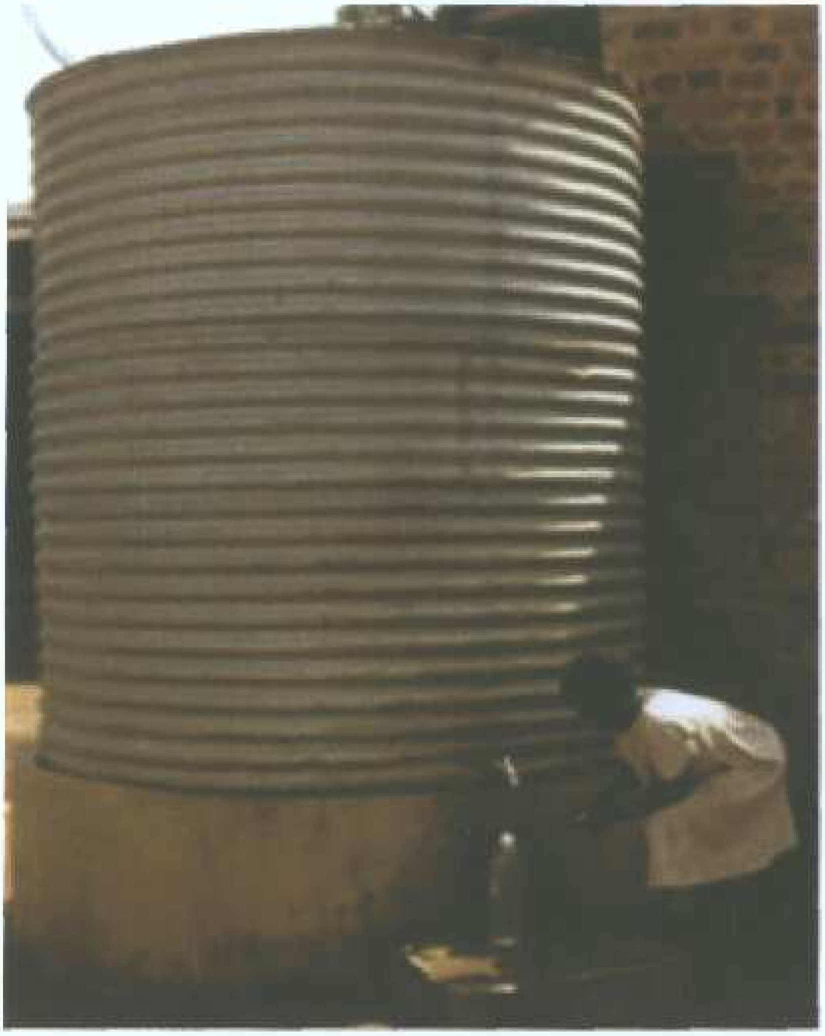


Figure 2.4: Metallic tank

Plastic tanks: These are made from plastic materials mainly manufactured by a local company and are termed as "crest tanks". These varied greatly in size ranging from 1000-10,000L. They would usually be surrounded by a concrete wall for protection purposes from dangers such as vandalism or piercing. The wall also protects them from direct sunlight which is believed to accelerate aging in plastic tanks.

Figure 2.5: plastic tank

Catchment ponds: These were ditches constructed behind a ground dam lined with a polythene sheeting to contain the water. A wall surrounding the entire ditch was built above the ground with an opening through which water was drawn (abstracted) using a small container tied on a rope/rod. These were usually roofed with iron sheets, however; the water collected from these roofs was diverted away from entering the catchment as it would be very dirty since these roofs were near to the ground and easily contaminated by animals and birds. Also, it would be expensive to put separate gutters to these small catchments to tap HRW from their own roofs.

Figure 2.6: Catchment pond being abstracted with a saucepan to fill up the PET bottle

All systems had covers on top with a small opening to let in HRW from the roof, however, the majority (98%) lacked sieves. All catchments (roof tops) were of iron sheets, however, these varied greatly in size and their surroundings. Many were surrounded by vegetation, mostly banana plantations, trees and other types of vegetation. These at times harbor weaver birds with their nests. All roof tops in this area are not cleaned (washed).

2.6 SURVEY OF HOUSEHOLDS DURING THE PRELIMINARY STUDY OF HRW

A preliminarily survey was carried out in 30 households which were engaged in harvesting rain water and already included in the first two months of study in which the microbial quality of water was assessed. The survey was designed to investigate whether

i. the community had ever heard about SODIS, whether they were practicing it already, other methods that were being used to treat drinking water as well as health and hygienic beliefs and practices.
ii. the community had ever been sensitized about harvesting rainwater, how they were handling it and whether they were using it for drinking with or without treatment.

The exercise involved carrying out interviews with the member of the household in charge of water supply. The questionnaire is described in Appendix 4.

2.7 TRAINING OF HOUSEHOLDS

Meetings were organized for training community members in SODIS water treatment. Mobilisation was made through the local leaders to invite people to attend these meetings. Meetings were scheduled at a time convenient to the community and located within a walkable distance for the majority of the households. People were invited and attended the trainings irrespective of owning a harvesting rainwater system.

Training began with sanitation and hygiene information and thereafter followed with SODIS facts. A SODIS demonstration was carried out after a thorough explanation and 2 to 5 members were given a chance to demonstrate it before the others. In between the demonstrations, members were given a chance to ask questions.

During training, explanations followed by demonstrations took place on how to clean and prepare used PET bottles before they use them for SODIS purposes by first removing the manufacturers' labels from these used bottles and thereafter wash them with soap for disinfection before rinsing them with clean water. The sanitation and hygiene training involved discussions with members about the organisms causing water borne diseases, the problems associated with drinking and using contaminated or untreated water, prevention measures for water borne diseases (for example proper disposal of waste, drinking treated water, proper handling-hand washing) and proper safe storage of treated water-storing water in clean closed containers. Thereafter members were asked to mention the methods they were using in their households and their respective challenges.

The SODIS training involved defining SODIS as a low cost point of use water treatment technology that involves the use of a PET bottle and solar energy. This was followed by steps involved in SODIS:

(i) Filling the bottle half way and shaking before filling it up and tightening it

(ii) Putting the bottle on a raised platform horizontally for 6 hours if the day is bright and for two days if cloudy, for example, during the rainy season.

(iii) Drinking the water directly from the bottles as summarized in Figure 1.7 (Chapter 1: section 1.5.1).

2.8 DISTRIBUTION OF PET BOTTLES

Polyethylene-terephthalate (PET) bottles (2L), with caps were purchased from Century Bottling Company Limited (Coca Cola), Jinja Road, P.O.Box 3990, Kampala-Uganda at a cost of 0.5 US dollars each. Each household was provided with four 2 liter PET bottles at the beginning of the study. These were replaced every 6 months as emphasized during the training.

2.9 YEAR LONG STUDY OF HRW

Fifty households took aprt in the year long study. Each household was given a number for identification H01– H50. All households were monitored once a month. The households were clustered into three groups of 15–17 households for sampling. Sampling was carried out during the first three weeks of each month. A different cluster was sampled each week. If members of a household were absent on the day of sampling, then that household would be revisited during the following week when sampling the other groups. On visiting the household a sanitary inspection form was first completed by the researcher. Samples of both raw and SODIS treated water were then collected. Physico-chemical parameters were measured on site. Samples for microbiological analysis were transported within 24 hours on ice to the laboratory at Makerere University for analysis.

2.9.1 *Sanitary inspection form*

A sanitary inspection form was designed following WHO (2011) guidelines and literature on HRW (Karim, 2010) and is described in Appendix 5: Harvesting rain water system sanitary inspection form. The form was completed during interviews, observations at the site and field data. The data were then recorded in excel for further analysis. The forms were completed for every visit in the first three months and thereafter once every three months.

2.9.2 *Categorization of HRW systems according to WHO (2011)*

WHO (2008) categorized household drinking water systems according to the microbial loads and the respective sanitary risk scores. Based on these, WHO (2008) further prioritized the required necessary actions accordingly as presented in Table 2.1. Systems were prioritized by noting the number of *E.coli*/100ml and the total score obtained from the first 10 questions on the sanitary inspection form as described in Table 2.1.

Table 2.1: Grid used for determining priority of remedial action for household drinking water systems based on a grading system of microbial quality and sanitary inspection ratio or scores

		Sanitary inspection risk score (susceptibility of supply to contamination from human and animal faeces)			
		0–2	3–5	6–8	9–10
E. coli classification (as decimal concentration/100)	< 1				
	1–10				
	11–100				
	> 100				

Low risk: no action required	Intermediate risk: low action priority	High risk: higher action priority	Very high risk: urgent action required

Source: WHO (2011)

2.10 PHYSICO-CHEMICAL PARAMETERS

The temperature, pH and total dissolved solids (TDS) of HRW samples were measured on site using a calibrated field pH/TDS meter (Hanna Instruments, S.L., Eibar, Spainmodel HI 9813-6N,). The meter was calibrated with 4.01 and 7.01 pH calibration buffer solutions (Hanna Instruments HI7004L and Instruments HI7007L). The tap on the HRW systems was opened and water was allowed to flow for 5 seconds before sampling the water in a beaker.The probe was dipped into the water and the values for temperature, pH and TDS were recorded following the manufacturer's instructions. Temperature was recorded in degrees Celsius (°C) and TDS in parts per million (ppm). The probe was then rinsed with distilled water.

2.11 RAINFALL MEASUREMENTS

Rainfall data was supplied by Sam Kagisagye a fellow Ph.D researcher funded by the Water is Life project (WIL). Daily total precipitation was recorded using three tipping bucket storage rain gauges (ONSET RG3) with a fully self-contained, battery-powered rainfall data collection and recording system. These were used at three locations within the project catchment area (Makondo sub-parish): Kiyumbakimu, Kiteredde and Michunda villages. HOBOware Pro software (Version 2.7.3 ONSET) and a water proof data shuttle were used for data processing, readouts and re-launch of the loggers. To obtain average rainfall for the study catchment area, precipitation computed at the three different rain gauge locations within the catchment area were averaged out on a daily, monthly and annual basis using the weighted averages (Thiessen) method (Shaw, 1994).

2.12 MICROBIOLOGICAL ANALYSIS

2.12.1 *Heterotrophic plate count (HPC)*

The total number of bacteria in a sample of water was determined using the pour plate technique according to WHO (2011). Samples of 1ml were placed in a Petri dish, poured with Yeast Extract Agar (Oxoid) and incubated at room temperature (27-30°C) for 24hours. All colonies were counted and the findings were expressed as total bacteria per ml (cfu/ml) of water.

2.12.2 *Thermotolerant coliforms*

Thermo-tolerant coliforms were determined using the membrane filtration technique (WHO, 2011). In this method, 100mls of water was filtered through 0.45-µm-pore-size and 47-mm-diameter Whatman cellulose nitrate membrane filters (GN-6 Metricel Grid, Gelman Sciences Inc. USA). The filters were then placed onto an absorbent cellulose pad (Gelman Sciences Inc. USA) in lauryl sulphate broth and incubated at 44.5°C for 24hours. All deep pink colonies were counted as presumptive thermo-tolerant coliforms and confirmation was done by use of EC medium at 44.5°C. The production of gas in inverted Durham tubes corfimed the presence of thermo-tolerant coliforms. The findings were expressed as thermo-tolerant coliforms / 100ml water.

2.12.3 *E. coli*

The presence of *E. coli* was determined using the membrane filtration technique (APHA, 2007). In this method, 100mls of water was filtered through 0.45-µm-pore-size and 47-mm-diameter Whatman cellulose nitrate membrane filters (GN-6 Metricel Grid, Gelman Sciences Inc. USA). The filters were then placed onto ChromoCult Coliform agar (CCA-Merck) and incubated at 37°C for 24 hours. All deep blue colonies were counted as presumptive *E. coli* colonies. A random sample of 5 colonies from ChromoCult coliform agar was plated onto Les Endo agar for confirmation. Red colonies with golden yellow sheen were confirmed as *E. coli*.

Positive control - *Escherichia coli (E. coli)* ATCC 25922, obtained from the clinical and laboratory standards institute (CLSI) through the Uganda National Bureau of Standards Microbiology Laboratory, Plot M217 Nakawa Industrial Area, Kampala Uganda, was used as a positive control in all tests. At least 3 plates of *E. coli* ATCC 25922 on a monthly basis were included in analysis.

2.12.4 *Faecal enterococci*

Faecal enterococci were isolated and enumerated using either the spread plate technique or the membrane filtration technique. In the case of the spread plate method, 0.1ml aliquots of sample were spread on Slanetz and Barltey Agar . For the membrane filtration method, a sample of 100mls was filtered through 0.45-µm-pore-size and 47-mm-diameter Whatman cellulose nitrate membrane filters (GN-6 Metricel Grid, Gelman Sciences Inc. USA) and placed on membrane enterococcus agar (Slanetz and Barltey Agar, HiMedia Ltd). All plates were pre-incubated at 35°C for 4 hours to aid bacterial resuscitation. The plates were then incubated at 44±0.5°C for a further 44 hours. After incubation all red and maroon colonies were counted and recorded as presumptive faecal enterococci. For confirmation, a filter was aseptically lifted from Slanetz and Barltey Agar and transferred to Bile EsculinAzide Agar (HiMedia Ltd). Plates were then incubated at 44 ± 0.5°C for 2 hours and a brown black colour around colonies confirmed faecal enterococci.

Positive control - *Enterococcus faecalis* ATCC 2921 was obtained from the clinical and laboratory standards institute (CLSI) through the Uganda National Bureau of Standards Microbiology Laboratory, Plot M217 Nakawa Industrial Area, Kampala Uganda and was used as a positive control in all tests. At least 3 plates of *Enterococcus faecalis* ATCC 2921 on a monthly basis were included in analysis.

2.12.5 *Clostridium perfringens*

The presence of *Clostridium perfringens* was determined by heating a sample of water (100mL) at 80°C for 15 min in a water bath to kill all non-spore forming bacteria. The pasteurized water was then filtered through 0.45-µm-pore-size and 47-mm-diameter Whatman cellulose nitrate membrane filters (GN-6 Metricel Grid, Gelman Sciences Inc. USA) and the filter was transferred to tryptose sulfite-cycloserin (TSC) agar plates (Oxoid CM0587) with the addition of TSC supplement (Oxoid-SR0088) and egg yolk (Oxoid-SR0047). The plates were incubated in an anaerobic jar, containing an aerocult A anaerobic System (Merck), at 35°C for 24 hours. Black colonies were counted as *Clostridium perfringens* colonies.

Controls: Positive *C. Perfringens* (UG-MUKVET 1.04) isolated from soil and obtained from the School of Vetirinary Medicine, Department of Biotechnology and Bio-safety Engineering, Makerere University, Uganda was used as a positive control in all tests.

2.13 COMPOUND PARABOLLIC COLLECTOR (CPC) METHODOLOGY

2.13.1 *The reactor*

All experiments were performed under natural solar radiation on a platform located at 0°20'15"N 32°33'51"E in the Makerere University-Uganda. The SODIS reactor as shown in Figure 2.7 was constructed by placing a glass tube at the linear focus of a CPC mirror with a W–E orientation; which was fixed to a metal stand raised 3 meters above the raised ground to recover maximum UV-A radiation during the day of experiment. The glass tube was made with an outlet valve in the bottom (for taking samples during experiments, and emptying the disinfection unit after use) and a removable methacrylate port at the top for filling the reactor (Figure 2.8 (a) and 2.8(b and table 2.4). The CPC reflector was made of highly reflective anodised aluminium transmittance material.

Figure 2.7: The 25L volume borosilicate glass tube reactor fitted with a compound parabolic collector (BGTR-CPC)

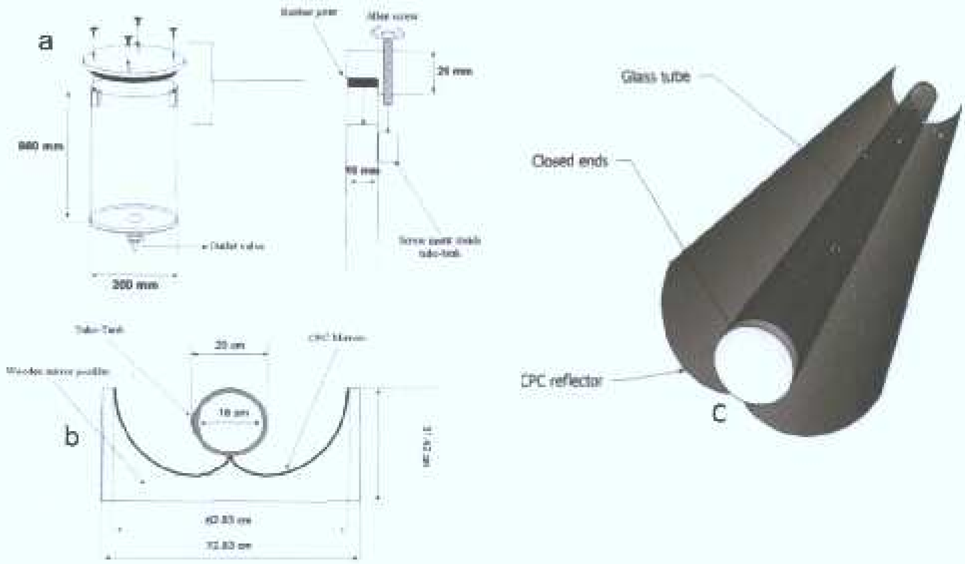


Figure 2.8: Diagram of (a) CPC-Tube (b) Its mirror dimensions and (c) Borosilicate glass tube reactor-CPC-BGTR

The glass tube was constructed with a diameter 20 cm and wall thickness of 1 cm to ensure the treatment of 25 L per batch. By using this CPC, the tube was homogeneously illuminated even on cloudy days. The top of the system that allows filing up of the system for experiments is secured using four Allen screws and a rubber seal. Raw water was poured in the unit through the top of the tank (Figure 2.8 (a)). Once the tank was filled with water, the top was closed with the screws and the rubber seal avoided any loss of water due to evaporation or further contamination of water from the environment. After the required exposure time to sunlight, treated water was removed using the exit valve at the bottom as shown in Figure 2.8

Table 2.2: Dimensions and properties of the enhanced borosilicate glass reactor

Tube	
Total volume	25L
Treated Volume	22.5L
Material	Borosilicate glass
External diameter	20cm
Thickness	1 cm
CPC mirrow	
Irradiated length	92.5cm
Irradiated width	62.5cm
Aperture area	$0.58m^2$
Concentration factor	1
Mirror surface	Highly reflective anodised aluminium. MIROSUN, Alanod, Germany

2.13.2 *Isolation and cultivation of the stock E.coli for the experiment*

A culture of a wild strain of *E. coli* was isolated from protected well water located in Kikoni slum 2km away from Makerere University. A sample of 100ml of raw water was filtered through 0.45-µm pore-size and 47-mm-diameter Whatman cellulose nitrate membrane filters (GN-6 Metricel Grid, Gelman Sciences Inc. USA).

Confirmed *E. coli* colonies were stabbed in Mueller Hinton agars which were preserved at room temperature for the further experiments. For every experiment, a culture from Mueller Hinton agar was streaked on nutrient agar and incubated at 37°C for 24 hours. A single colony was then inoculated at 37°C into 100mL sterile nutrient broth (Conda Pronadisa 1340) at 37°C for 18-20 hours to atain a stationary phase. Cells were harvested by centrifugation (Eppendorf AG 22221, Germany) at 800g for 10 min. The pellet was washed three times in quarter strength Ringers and resuspended in 5 ml ringers solution. The stationary phase of bacterial growth yielded a concentration of 10^5CFU/mL-10^7CFU/mL. For all experiments, the range of initial concentrations (C0) of *E. coli* was 10^5–10^7 CFU/100mL.

To avoid climbing to access the CPC at 3M high every hour of sampling, a rubber tube of internal diameter 5mm and 3m long was connected to the outlet. A volume of $100cm^3$ was always abstracted before taking the real sample to ensure that the actual sample originate from the CPC instead of the stored water in the rubber tube.

2.13.3 *Enumeration of E. coli during the experiment*

Enumeration of bacteria contained in the borosilicate tube exposed to sunlight was conducted through the standard plate count method after a series of 5 fold dilutions for time t_0 to t_4. Volumes of 0.1 mL of the approximately diluted sample were spread on chromocult agar (CCA) agar plates in triplicate and incubated at 37°Cfor 24 hours. Deep blue colonies were counted as *E. coli*. For time t_4 to t_7 and those after t_7, 100mls were filtered through 0.45-μm-pore-size and 47-mm-diameter Whatman cellulose nitrate membrane filters (Sartorius,Vienna, Austria). For enumeration of *E. coli*, filters were placed onto CCA plates and incubated at 37°C for 24 hours in a Paqualab 25 incubation kit.

Dark controls involved taking a sample of water at time zero (at the start of experiment) and keeping it in the dark until the end of the experiment before testing for *E.coli*.. The possibilityof regrowth after water treatment was investigated by keeping part of the last sample at room temperature under dark conditions for 24 hours before testing for *E.coli* .

Water

In order to carry out experiments under natural water conditions and to avoid weakening of bacterial cells due to an unfavourable osmotic environment (lack of ions), natural well-water that had not undergone autoclaving was used during all the experiments (McGuigan *et al.*, 2012). Water was collected from a well located in a heavily populated slum area (0°20'11"N 32°33'51"E) near Makerere University the day before the experiment. The concentration of naturally occurring *E. coli* was determined by filtering 100 mL through 0.45-μm-pore-size and 47-mm-diameter Whatman cellulose nitrate membrane filters and enumerated using CCA agar, and were in the range of 100–400 CFU/100 mL of *E.coli*.

Measurement of natural solar radiation and temperature

Solar UV irradiance was measured with a global UVA+B radiometer (Solartech, USA). The radiometer was pointed in the direction of available sunrays. The temperature of samples that were withdrawn at hourly interval from the CPC were measured using a calibrated laboratory thermometer (modelHI 98 509-1, HannaInstruments, S.L., Eibar, Spain) to determine if mild thermal inactivation contributed to inactivation rates observed.

2.14 STATISTICAL ANALYSIS

2.14.1 *Statistical tests*

Mean and median were calculated in excel 2010 while the Pearson Chi-square, One-Way Analysis of Variance (ANOVA), the pairwise t-test and tree analysis were run in SPSS PASWStatistics17.

2.14.2 *Tree analysis*

Tree analysis was used to investigate the relationship between a range of social and environmental factors and the numbers of either *E.coli* or faecal enterococci in the HRW. SPSS PASWStatistics17 software was used to generate the results. The variables investigated are listed in Table 2.3 together with the codes used for the analysis.

Table 2.3: List of variables and codes used when investigating the influence of social and environmental conditions on bacterial numbers in HRW using TREE analysis

Variable	Characteristics	Codes used
Condition of drainage of water collection area	Good	1
	Poor	2
Cleaning/first rain flush out of the HRW system	No	2
	Yes	1
Design	Below ground	2
	Above ground	1
Dirty or blocked gutter	Clean	1
	Dirty	2
Holiday/schooling time	Holiday	2
	School	1

Highest level of education for the head of family	None	3
	Primary	2
	Secondary	1
Mode of abstraction	Dipping using smaller containers (faulty tap)	2
	Tap	1
Number of rainfall events in a month	4-11	1
	>11-18	2
	>18	3
Number of days between the last two rainfall events		3
	0-3 events	
	4-6	2
	>6-30	1
Number of days between the last rainfall event and the day of sampling		3
	0	
	1-3	2
	>3-28	1
pH	4.8-6.4	1
	6.5-7.8	2
	7.9	3
Presence of overhanging vegetation	>4m	1
	≤4m	2
Presence of pit latrine close to HRW system		2
	>15m	
	≤15m	1
Presence of birds or roaming animals	None	1
	Animals or birds	2
Rainfall amount received in a month	2.9-12.9mm	1
	>12.9-64.7mm	2
	>64.7-135.7mm	3
Size of household using HRW system	≤6	1
	>6 and sharing	2
Season	Wet	2
	Dry	1
TDS	0-50mg/l	1
	>50-287mg/l	2
Temperature	19.5-24	2
	24.1-33.6	1
Type of HRW system material	Catchment	4
	Concrete	3
	Metallic	1
	Plastic	2
Volume remaining	≤1/4	3
	>1/4-1/2	2
	>1/2	1
Volume of the HRW system	500-3,000l	1
	>3000l-30,000l.	2

*TDS-total dissolved solids

SPSS PASWStatistics17 was used to carry out the TREE analysis. The dependant variable (microbial indicator of contamination) was compared with the independant variables. The programme generates tree diagrams with nodes as described in Figure 2.9. Node 0 describes the dependent variable – *E.coli* or faecal enterococci. The most significant factor emerges at the top of the tree and the initial nodes one and two describe how this variable impacts on the dependent variable. Then the next most significant factor emerges. In this study only factors with a P value of ≤ 0.01 are described in the results. A backward stepwise removal of factors led to the generation of further TREE models i.e. following the generation of the first TREE model, the most significant factor was removed from the analysis to generate a further TREE model and so on until the significance of the values obtained exceeded a p-value of 0.01.

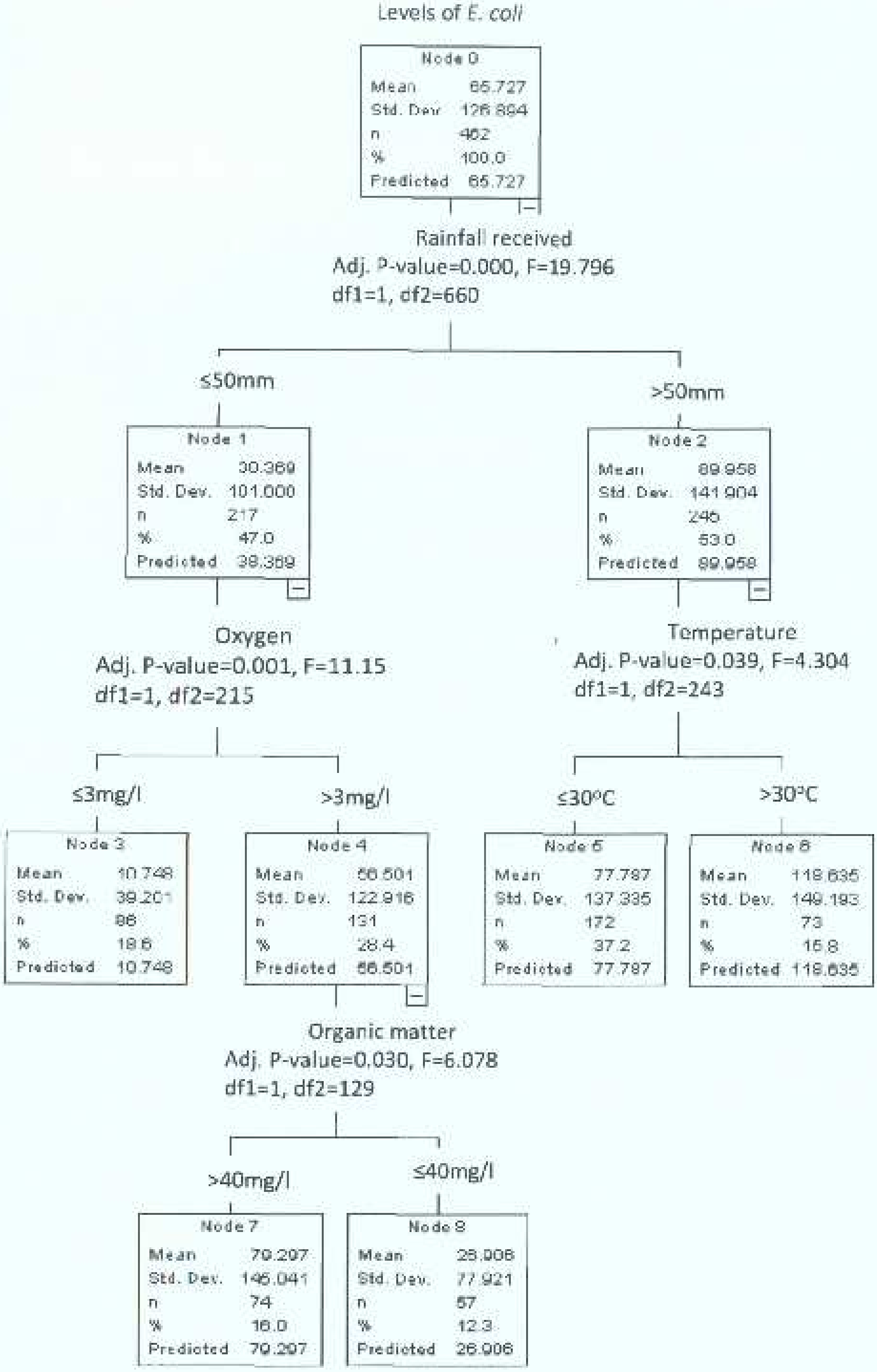


Figure 2.9: Tree diagram (model) generated

3 RESULTS

The quality of HRW in the Mokondo region had never previously been studied. Households with harvested rainwater tanks were invited to participate in the study and a preliminary investigation was carried out to establish the base-line quality of the water. The results of this study are presented in Section 3.1. Based on these findings, a year-long study was carried out to study the quality of HRW throughout wet and dry seasons. The microbiological quality of the water was investigated and SODIS was used to treat non-potable water and the findings are presented in Section 3.2. Finally an investigation was carried out in Kampala to evaluate the impact of solar disinfection of *E. coli* using a 25L borosilicate glass batch reactor fitted with a compound parabolic collector (Section 3.3).

3.1 PRELIMINARY INVESTIGATION OF THE QUALITY OF HARVESTED RAINWATER IN MOKONDO AND THE EFFECTIVENESS OF SODIS FOR THE TREATMENT OF THE WATER

Thirty households participated in the preliminary study. The households were selected following visits to the community and discussions with the local leaders and facilitators. Inclusion of a household in the survey was determined by factors such as interest of the household in the project, size of the household and willingness to participate.

3.1.1 *Response of households to questionnaire*

Questions were put to the households to gain an insight into the circumstances of the households, their views of the harvested rainwater and their knowledge of risks associated with contaminated rainwater (Appendix 4: Questionnaire Designed to Check the Awareness Level Regarding the SODIS (Solar Water Disinfection) Technique). The findings of the study are presented under the headings family size and socio economic status, health, water usage, HRW – use and cost, water safety and water treatment.

Family size and socio economic status

The number of members in a household varied from less than 5 people in the minority of the households (27%) to more than 9 people in some households (20%). The majority of the households (53%) had between 6 and 9 people (Figure 3.1a). The highest level of education attained was secondary level for 40% of the people in the households. The majority (53%) of the people reported to have attained primary level while only 7% reported to have not gone to school at all (Figure 3.1b).

Varying levels of income among the 30 HRW households studied were recorded. The majority of the households (43%) reported to be earning between 100,000 and 200,000 Ug Shs. One third of the households earned less than 100,000 Ug Shs (about 40 US $) per month and others (24%) earned more than 200,000Ug Shs (80US $) per household.

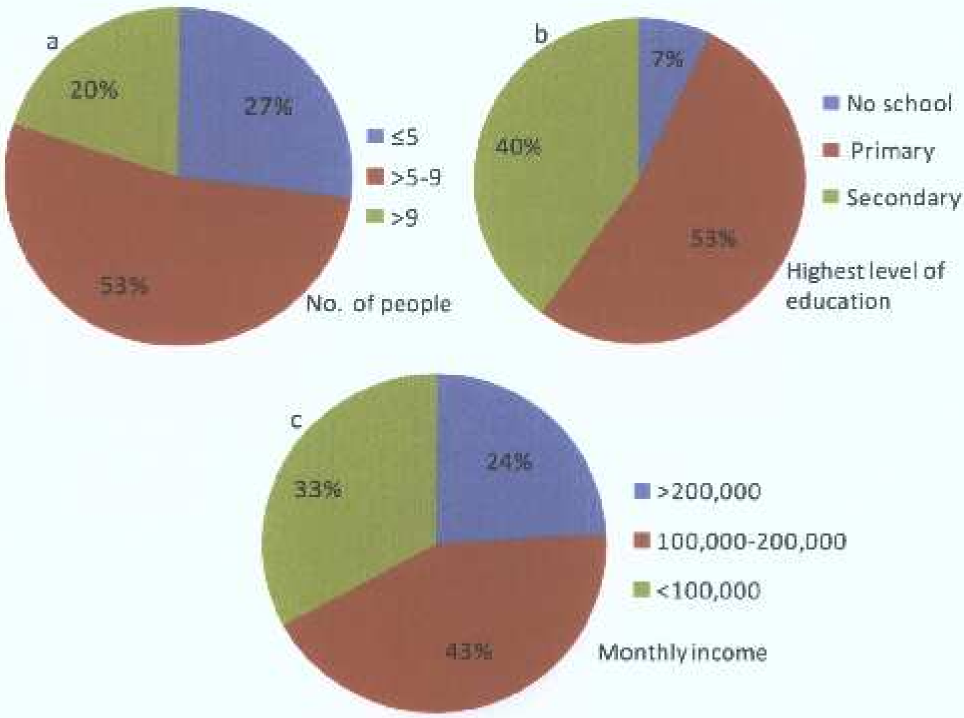


Figure 3.1: Family size and socio economic status of households involved in the preliminary study.: a- Number of people per household; b- Highest level of education attained in the household, c- Monthly income (UgShs) of studied households.

Health Status

Among the most common diseases reported were gastro-trouble, typhoid and fever (Figure 3.2a). The majority (40%) reported fever followed by gastro-trouble (37%) and typhoid (23%).

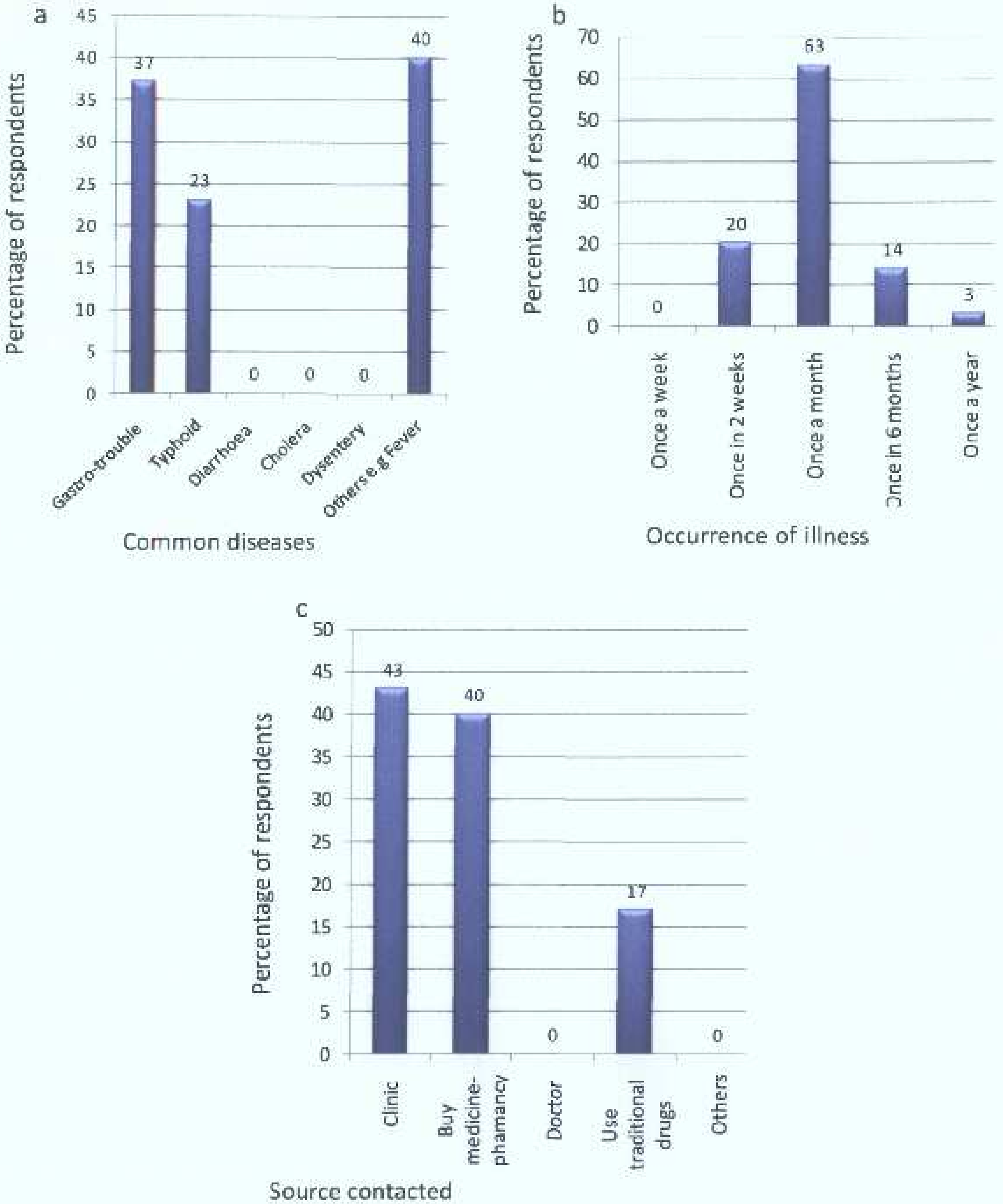


Figure 3.2: The health status of study participants in Makondo: a- The common diseases, b- Rate of occurrence of illnesses in households, c-Sources contacted for medication following illness

Other illnesses which are known to be water borne for example cholera, dysentery or diarrhoea were not reported by any respondent. When questioned about the frequency of illness, the majority of respondents (63%) reported being ill once in a month. Others experienced illness once in two weeks (20%), once in six months (14%) and a few (3%) once a year (Figure 3.2b). When ill most consulted clinics or pharmacies and some used traditional drugs. None reported seeing a doctor (Figure 3.2c).

Water Usage

The majority (70%) of the households interviewed reported using between 10-15L of water per person per day. Households watering animals used more. All the 30 households interviewed were using HRW mainly for drinking. When HRW was unavailable, the majority sourced water from boreholes and protected wells. A smaller number used water from unprotected wells as shown in Table 3.1 below.

Table 3.1: Sources of water used in the absence of HRW

Water sources	No. of respondents (%)
Hand pump	27 (90%)
Protected well	20 (67%)
Un protected well	7 (23%)

HRW – use and cost

All the households interviewed in the survey had HRW systems. While all households used the HRW mainly for drinking, other uses included watering animals and washing (Figure 3.3a). However, use for animals was restricted to the rainy season when the HRW was in excess.

The cost in Uganda shillings involved in installing the HRW tanks varied. Many (23%) of the households got the systems free from the local NGO (MMM). Nearly half of the households reported the cost to vary from 300,000-700,000 Ug Shs and a third of the households reported the cost to have exceeded 700,000 Ug Shs as shown in Figure 3.3b below. It was also noted that the cost increased with the size of the tank.

All households considered harvesting rainwater to be a good mitigation practice to water scarcity and they also valued time saved. Of the 30 households practicing HRW, 70% reported saving more than 3 hours a day and others saved 2-3 hours a day as summarized in Figure 3.3c below. Time saved was used by most (77%) for farming and others used the time for social activities.

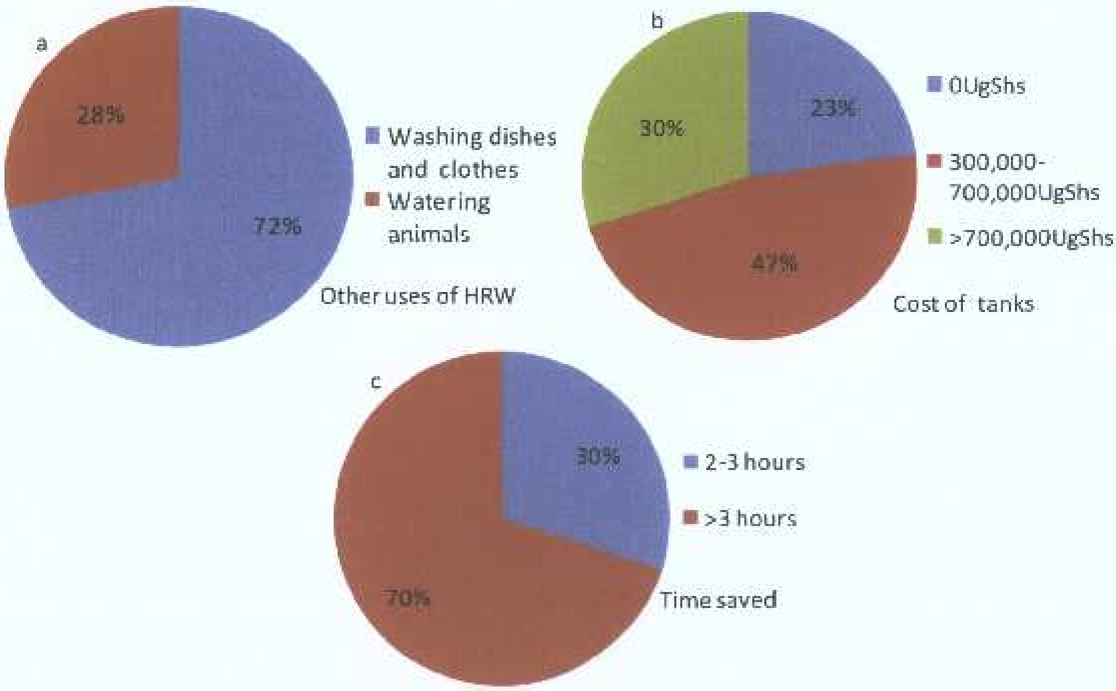


Figure 3.3: The uses of HRW, cost involved and the advantages of HRW: a- Other activities in which HRW is used other than for drinking, b- The cost of installing a HRW system and c- Time saved when a household has HRW available.

Water safety

Out of the 30 households that were interviewed, 16 (53%) felt that the water they were using was not safe for drinking. Only 5 (17%) households felt they were using safe drinking water while 9 (30%) households were undecided. The majority (77%) of the interviewed households reported to have been consulted about the awareness of safe drinking water. Only 33% of the respondents reported not to have been consulted about the safety of drinking water.

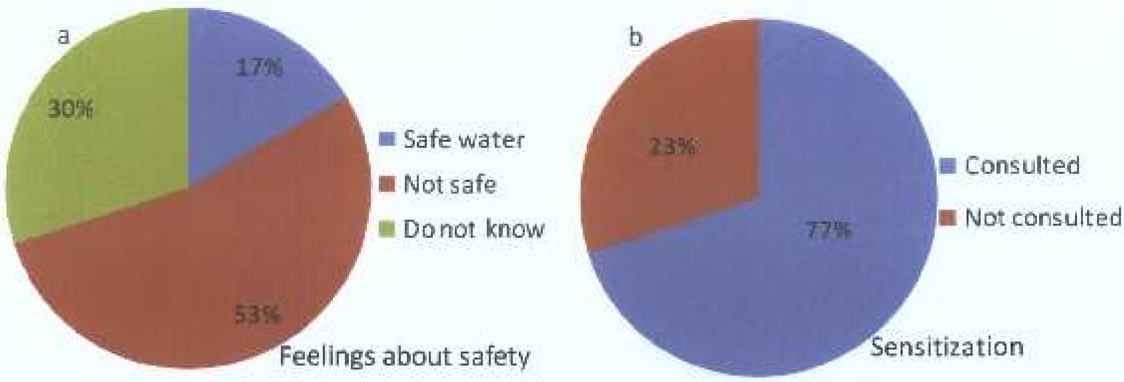


Figure 3.4: Knowledge of the safety of HRW: a-The different feelings about the safety of drinking water respondents, b-HRW users who were ever consulted/sensitized about the safety of drinking water

A number of sources of sensitization about the safety of drinking water among the HRW users were reported as shown in Figure 3.5. The majority (61%) were made aware of water safety by NGOs and some by students/volunteers. Few were made aware by Government officials. None of the respondents reported to have been consulted by private agencies.

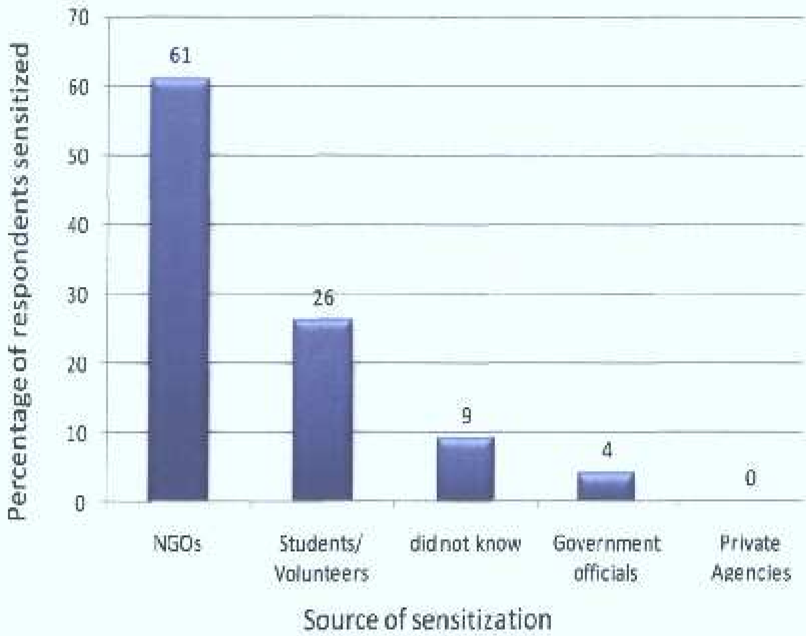


Figure 3.5: Source of information about the safety of drinking water

Water treatment

One third of the households reported treating water before drinking (Figure 3.6).

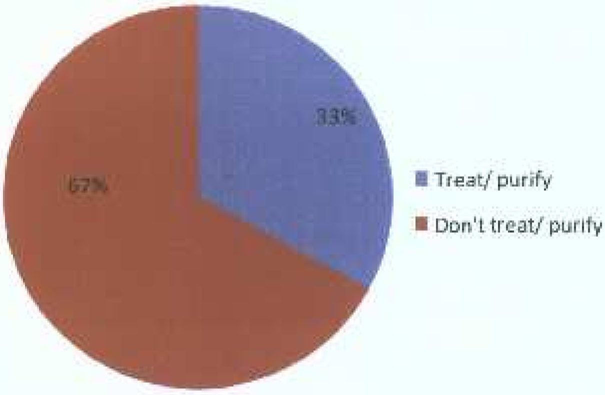


Figure 3.6: The HRW users who practice some form of drinking water treatment or purification

Eight of these households used boiling and two used water guard (chlorine tablets). None of respondents reported using SODIS, filtration or any other method of treatment or purification as shown in Figure 3.7.

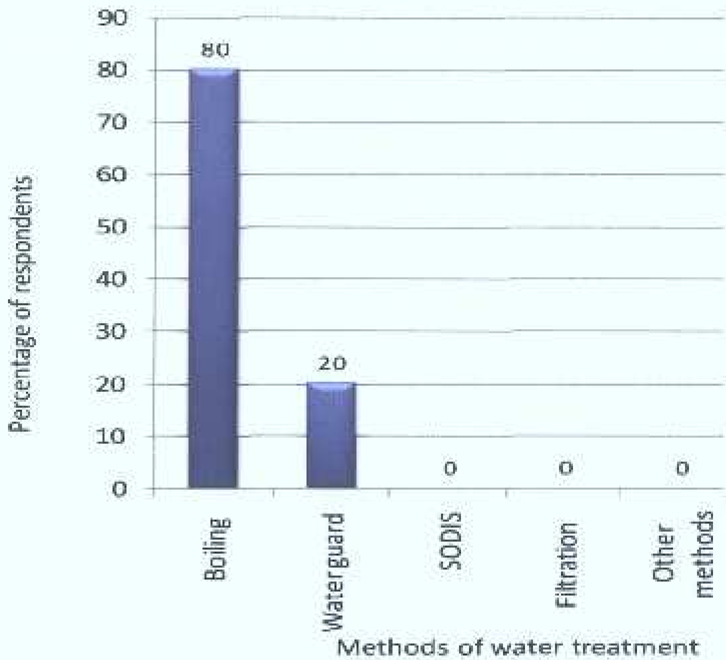


Figure 3.7: Methods of water treatment /purification at households

Respondents reported different feelings about the taste of drinking water after treatment. The majority reported the taste to be good (46%) while 36% reported it to be bad. Only 18% of the respondents reported it to be very good, however, none said it to be poor as shown in Figure 3.8 below.

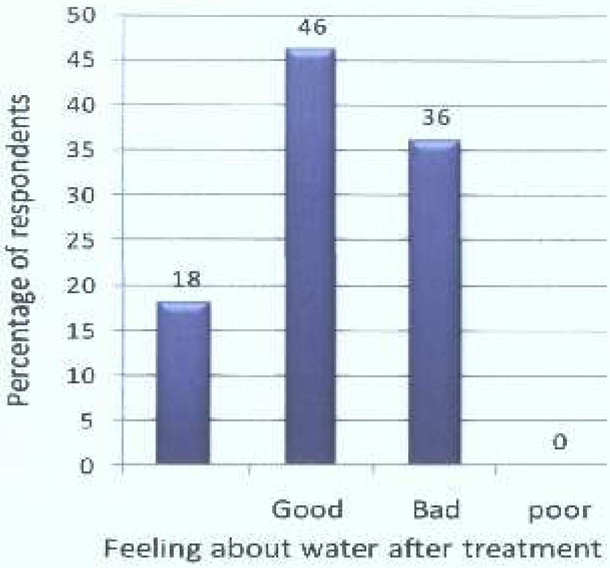


Figure 3.8: The different feelings about the taste of water after treatment

Knowledge of SODIS

None of the households had ever used SODIS and only one had heard of it .All the 30 households which were invited for the workshop attended the training.

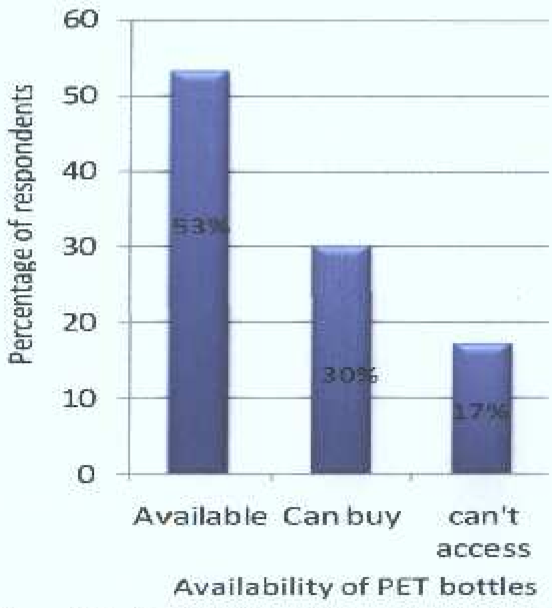


Figure 3.9: Availability of transparent plastic (PET) bottles

When respondents were asked about the availability of bottles, 53% reported that the bottles were available. 30% of the respondents reported that they were willing to buy them. Only 17% reported that the PET bottles were not available as shown in Figure 3.9 above.

All the households reported receiving sunlight throughout the day on sunny days especially during the dry seasons. However, on cloudy days the amount and duration of sunlight in a day varied a lot.

3.1.2 *Types of HRW systems studied*

The types of HRW system used varied and included metallic, plastic and concrete tanks and some catchment ponds. The systems were dispersed throughout the region (Figure 3.10).

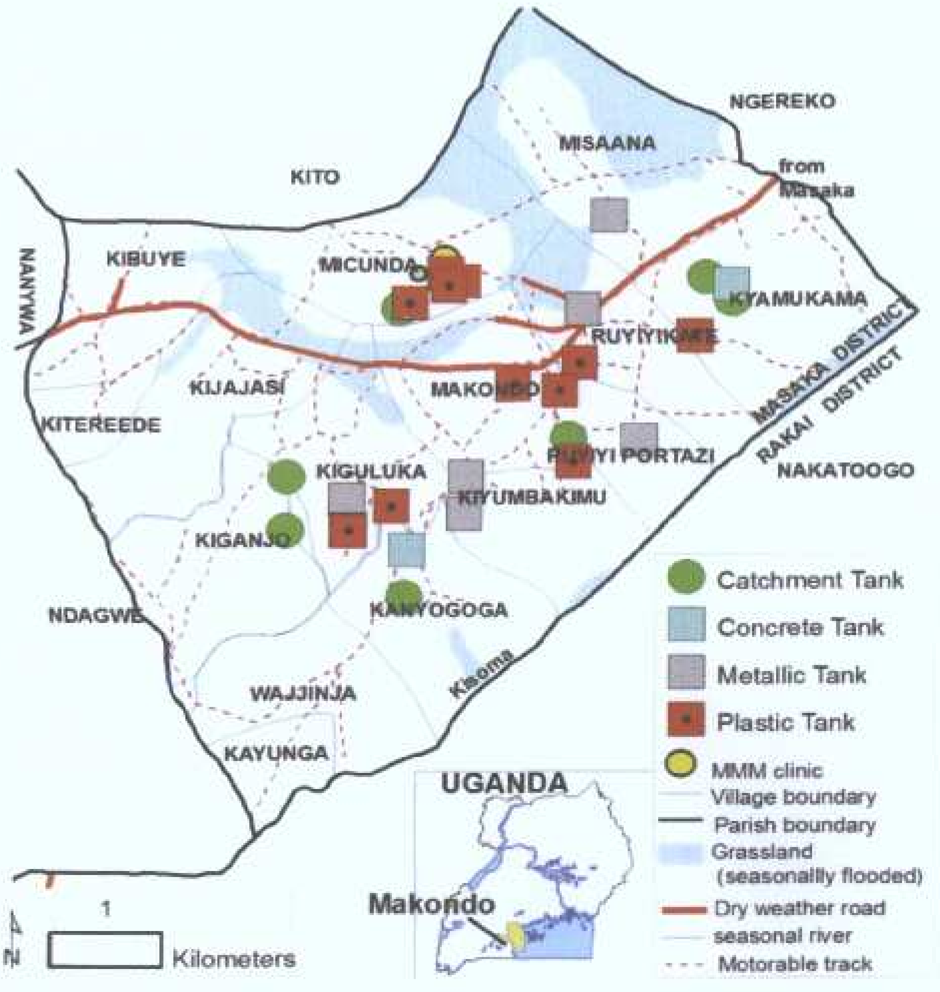


Figure 3.10: The study area in Mokondo where the preliminary investigation of the HRW quality was conducted. The sampling sites together with the HRW system type are noted on the map.

3.1.3 *Rainfall data for April – July 2011*

The study was designed to cover both wet and dry months to get an overview of seasonal changes. It was carried out in April and May 2011 which were wet months and in June and July 2011 which were dry months. Rainfall amount during these four months is described in Table 3.2.

Table 3.2: Rainfall data for Makondo sub-parish-Masaka-Uganda April – July 2011

Month	Average Daily Rainfall [mm]	Monthly total rainfall [mm]	Daily Range [mm]
April 2011	5.01±32.1	143.1	0-23
May 2011	2.72±6.2	83.9	0-26.4
June 2011	0.02±0.1	0.7	0-0.2
July 2011	0.9±3.3	27.8	0-17.8

The daily amount of rainfall ranged between 0-26mm during April and May 2011 and the total monthly rainfall was 143.1mm and 83.9mm for April 2011 and May 2011, respectively. April marked the beginning of the first rainy season in the year following the dry season January – March. The daily amount of rainfall ranged between 0-0.2mm during June 2011 and 0-17.8mm during July 2011. Despite the fact that June and July 2011 were generally dry months, the total monthly rainfall was 0.7 and 27.8mm for June and July, respectively. June marked the beginning of the second dry season in the year.

3.1.4 *Quality of the HRW during the wet season*

During the wet months, the temperature of the water ranged from 19.5°C to 28.2°C. The levels of dissolved oxygen in the water ranged from 2.4 to 7.6mg/l and the mean pH was neutral. The total dissolved solids (TDS) ranged from 5 to 46 mg/l (Table 3.3).

Table 3.3: Physico-chemical parameters of the harvested rainwater during April and May 2011

Parameter	Minimum		Maximum		Mean		Median	
	April	May	April	May	April	May	April	May
Temp [°C]	20.9	19.5	27.8	28.2	23.5±2.1	22.5±18	22.6	21.9
DO [mg/l]	2.4	2.4	6.1	7.6	3.9±0.9	4.6±1.1	3.9	4.5
pH	5.3	5.6	7.9	8.5	7.3±0.8	6.9±1.3	7.3	7.1
TDS [ppm]	5	6	43	46	12.5±9.3	12.9±8.8	9	10.0

Temp-Temperature, DO-Dissolved oxygen, TDS-Total dissolved solids

The microbiological examination of the water included investigations on the heterotrophic plate count (HPC), thermotolerant coliforms (TTC), *Escherichia coli* and faecal enterococci. The minimum number of organisms detected was 160cfu/ml for the total bacterial count. In the case of the thermotolerant coliforms, of indicator bacteria *E. coli* and faecal enterococci, none was detected in some systems indicating that these systems had potable water. However, in many systems a high number of organisms, >400cfu/ml, was detected in all categories tested. The presence of *Escherichia coli* and faecal enterococci indicated that the water was non-potable and depending on the indicator organism used this ranged from 71.9% - 100% of the HRW systems (Table 3.4).

Table 3.4: Microbial parameters of the harvested rainwater during April and May 2011

Parameter	Minimum		Maximum		No. non-potable system	
	April	May	April	May	April	May
HPC [cfu/ml]	160	160	$>10^4$	$>10^4$	-	-
TTC [cfu/100ml]	0	1	>400	>400	-	-
E. coli [cfu/100ml]	0	0	>400	>400	22(73%)	23(71.9%)
Faecal enterococci [cfu/100ml]	0	1	>400	>400	27(90%)	32(100%)

HPC-Heterotrophic plate count, TTC-Thermal tolerant coliforms, cfu-colony forming units.

Note: In May, 32 HRW systems were sampled because two of the households recruited had 2 different HRW systems of different material, and size and the users requested to know the microbial quality of both.

3.1.5 *Quality of the HRW during the dry season and the use of SODIS*

During the dry season, some of the households did not have HRW and so other water sources used by the household such as bore holes and open dug wells were analysed. The values for temperature, dissolved oxygen, pH and total dissolved solids for all the systems are described in Table 3.5. The values for the HRW were similar to those for April and May. The temperature ranged from 20 to 29°C. The average pH was just below neutral and the maximum TDS was 129. In the case of the boreholes and wells, the temperature was higher and ranged from 27.8 to 29.3°C. The pH was again near neutral and the maximum TDS was 193. None of physico-chemical parameters showed a significant difference ($p>0.05$) between June and July.

However, in both months the TDS of other sources of water was significantly ($p<0.05$) higher than that of HRW.

Table 3.5: Physico-chemical parameters of the harvested rainwater (HRW) and water from other sources (OS) during June and July 2011

Parameter	HRW					
	Temp. [°C]		pH		TDS [mg/l]	
	June	July	June	July	June	July
Minimum	20	23	4.8	4.2	0	8
Maximum	28.9	29	7.3	7.4	85	129
Mean	24.9±2.4	26.2±1.6	6.0±0.1	6.6±0.7	26.2±26.1	25.5±25.1
Median	25.4	26.7	5.8	6.7	13	17.5
Other sources of water-OS (boreholes and wells)						
Minimum	27.8	27	5.3	4.4	42	48
Maximum	29.3	29.3	6.4	7.5	193	87
Mean	28.7±0.7	27.9±0.9	5.7±0.5	5.9±1.3	99.3±65.4	65.6±16
Median	28.75	27.7	5.55	6.3	81	68

Temp-Temperature, Do-Dissolved oxygen, TDS-Total dissolved solids, ±standard deviation

A number of systems sampled in June and July 2011 consistently had contaminated water that was unsafe for drinking (Table 3.6 and Table 3.7). However, there were generally lower levels of *E. coli* and faecal enterococci than in the wet months. Given the levels of microbiological contamination detected in the HRW during April and May, the use of SODIS to treat the water was investigated. The response of the water to SODIS was monitored by determining the presence of *E. coli* and faecal enterococci in the water before and after treatment. Following SODIS treatment, the water samples showed significantly ($p<0.05$) lower levels of contamination for both *E. coli* and faecal enterococci (Table 3.6 and Table 3.7). The HRW and the water from other sources responded well to SODIS treatment. While >75% treatment efficiency was achieved in the field, the treatment efficiency was improved and was significantly ($p<0.05$) higher when the water was treated at the University in Makerere in June (Table 3.6). Faecal enterococci significantly ($p<0.05$) recorded higher treatment efficiency than *E. coli* in both HRW and other sources of water.

Table 3.6: Microbial parameters of HRW and water from other sources before and after SODIS treatment in the field and at Makerere University during June 2011 (dry month)

Microbial parameter	n	Range cfu/100ml	No. potable (%)	N	Range cfu/100ml	No. potable (%)	n	Range cfu/100ml	No. potable (%)
Raw Harvested rainwater (HRW)				Treated From Makondo (field conditions)			Treated From Makerere University roof (laboratory conditions)		
E. coli	21	0-75	8(38%)	21	0-29	16(76%)	20	0-1	19(95%)
Faecal enterococci	21	0-154	5(25%)	21	0-14	17(81%)	20	0-0	20(100%)
Other sources of water-OS (boreholes and open dug wells)n=4				Other sources of water-OS (boreholes and open dug wells)n=4			Other sources of water-OS (boreholes and open dug wells)n=4		
E. coli	4	0-35	1 (25%)	4	0-6	3(75%)	4	0-0	4 (100%)
Faecal enterococci	4	0-2	2 (50%)	4	0-1	3(75%)	4	0-0	4 (100%)

n-sample size, No.-Number

Table 3.7: Microbial parameters of HRW and water from other sources before and after SODIS treatment in the field during July 2011 (dry month)

Microbial parameter	N	Range cfu/100ml	No. non-potable (%)	No. Potable (%)	n	Range cfu/100ml	No. non-potable (%)	No. Potable (%)
Raw Harvested rainwater (HRW)					Treated Harvested rainwater			
E. coli	26	0->400	16 (61%)	10(39%)	26	0->400	9(34.6%)	17(65%)
Faecal enterococci	26	0->400	18(69.2%)	8(31%)	26	0-36	5(19.2%)	21(81%)
Other sources of water-OS (boreholes and open dug wells)(n=5)					Other sources of water-OS (boreholes and open dug wells) (n=5)			
E. coli	5	2->400	5 (100%)	0(0%)	5	1->400	5(100%)	0 (0%)
Faecal enterococci	5	0-69	4(80%)	1(20%)	5	0-53	2(40%)	3 (60%)

n-sample size, No.-Number

3.2 YEARLONG STUDY OF THE QUALITY OF HARVESTED RAINWATER IN MOKONDO MASAKA-UGANDA AND THE EFFECTIVENESS OF SODIS FOR THE TREATMENT OF THE WATER

The preliminary study had indicated that the majority of HRW systems were contaminated and unfit for drinking. SODIS was shown to be an effective method to treat the water. It was of interest to carry out a year- long study to determine the influence of climate (seasons) on the quality of the HRW. This study was carried out from August 2011 to August 2012. Up to 50 households were involved and their location is described in Figure 3.1. Of the 50 households (HRW systems), 30 Households (systems-H01, H02, H03, H04, H06, H07, H08, H10, H14, H15, H16, H18, H19, H20, H21, H24, H25, H26, H27, H27, H31, H32, H32, H33, H36, H43, H44, H46, H47, H48) also participated in the preliminary study.

As with the preliminary studies, the types of HRW systems varied and included catchment, concrete, metallic and plastic systems. Physicochemical parameters measured included temperature, pH and TDS as in the earlier study. The microbiological quality of the water was tested before and after SODIS treatment for the indicator bacteria *E. coli* and faecal enterococci. The water was also tested for *C. perfringens*. A sanitary inspection was carried out every time water was sampled to determine the relationship of the water quality with a range of social and environmental conditions.

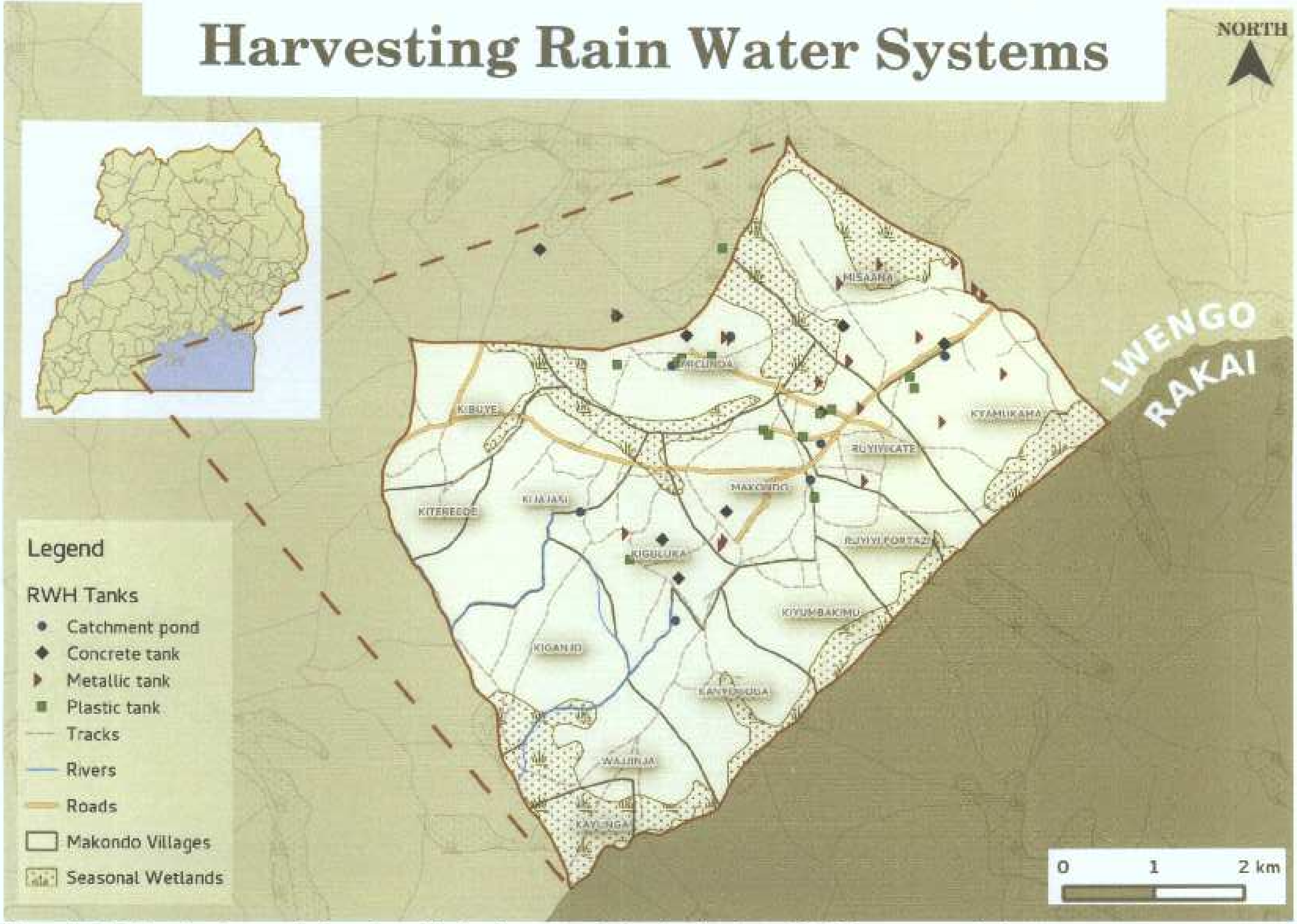


Figure 3.11: Map showing makodo sub-parish (study area) and the distribution of HRW systems studied

3.2.1 *Rainfall*

Uganda is known for two rainy seasons and two dry seasons in the year. September to November is known as the longest rainy season followed by the longest dry season in the year which extends from December to March. April and May is another rainy season in the year while June, July and August represent another dry season, however, these two seasons are generally shorter lasting for only 2-3 months. The average daily and total monthly rainfall values during the study period are described in Table 3.8.

Table 3.8: Shows the average monthly amount of rainfall in Makondo Masaka-Uganda during the study period (August 2011 to August 2012)

Month/Year	Daily Range [mm]	Total monthly rainfall [mm]
	Dry season	
Aug. 2011	0.0-27.8	43.3
	Rainy season	
Sept. 2011	0.0-12.4	64.7
Oct. 2011	0.0-36.5	135.9
Nov. 2011	0.0-29.4	81.6
	Dry season	
Dec. 2011	0.0-8.2	32.1
Jan. 2012	0.0-1.9	5.3
Feb. 2012	0.0-2.3	12.9
	Rainy season	
Mar. 2012	0.0-10.9	44.2
April. 2012	0.0-13.3	64.4
	Dry season	
Jun. 2012	0.0-0.8	2.9
July. 2012	0.0-3.0	4.2
Aug. 2012	0.0-7.8	24.2

Throughout the study, the monthly total rainfall ranged from 2.9mm to 135.9mm. October 2012 had the highest monthly total rainfall of 135.9mm followed by November 2012 (monthly total rainfall of 81.6mm). It was noted that, rainfall amounts in a rainy season followed a normal distribution curve. That is to say it started with low volumes during the first months followed by a peak in the middle of the season and there after decreased to very low amounts at the end of the season as described in Table 3.8.

January 2012, February 2012, June 2012 and July 2012 were typically dry months with very low amounts of rainfall. During the study period, June recorded the lowest total monthly rainfall (2.9mm) followed by July 2012 in which only 4.2mm in a month.

In spite of the fact that August is known to be a dry month with very low amounts of rainfall, August 2011 received a reasonable amount of rainfall (43.3mm) compared to August 2012 which received only 24.2mm. Of all the months in the rainy season, August 2012 received the least rainfall amount (24.2mm).

Despite the fact that March is usually known to be a wet month marking the beginning of the MAM rainy season, there was a very low amount of rainfall, which qualified it to be a dry month. March 2012 recorded a monthly total rainfall of 44.2mm. The unusual total monthly rainfall received in March, August and December could be due to effects of climate change.

3.2.2 *Physico-chemical parameters of raw HRW*

The physico-chemical parameters investigated on in the current study were temperature, pH and TDS. The preliminary study had shown that the values obtained for these parameters did not change following SODIS and so only values for the raw water were recorded during the yearlong study.
As described in Figure 3.12 temperature ranged from 19.5°C in October 2011 and March 2012 to 33.6°C in December 2011 and April 2012, with a mean value of 26.7°C. There was no significant difference ($p=0.07$) in temperature between the wet and dry months. Temperature did not also show a significant difference ($p=0.09$) among the defferent systems as shown in Appendix 6: Variation of temperature in the different harvesting rainwater collection systems. As shown in Figure 3.12 the pH of the HRW systems was generally around neutral. It ranged from 4.8 in November 2011 to 9.5 in August 2011 with an average of 6.9±0.7. The variation of pH among the different systems is described in Appendix 7: Varriation of pH in raw harvested rain water. However, pH did not show a significant association ($p=0.08$) with the defferent systems. TDS varied between the systems and ranged from 0mg/l in November 2011 to 287mg/l in March 2012 with an average of 36.1±41.0. The variation of TDS among the different systems is detailed in Appendix 8: Variation of TDS in raw harvested rainwater.

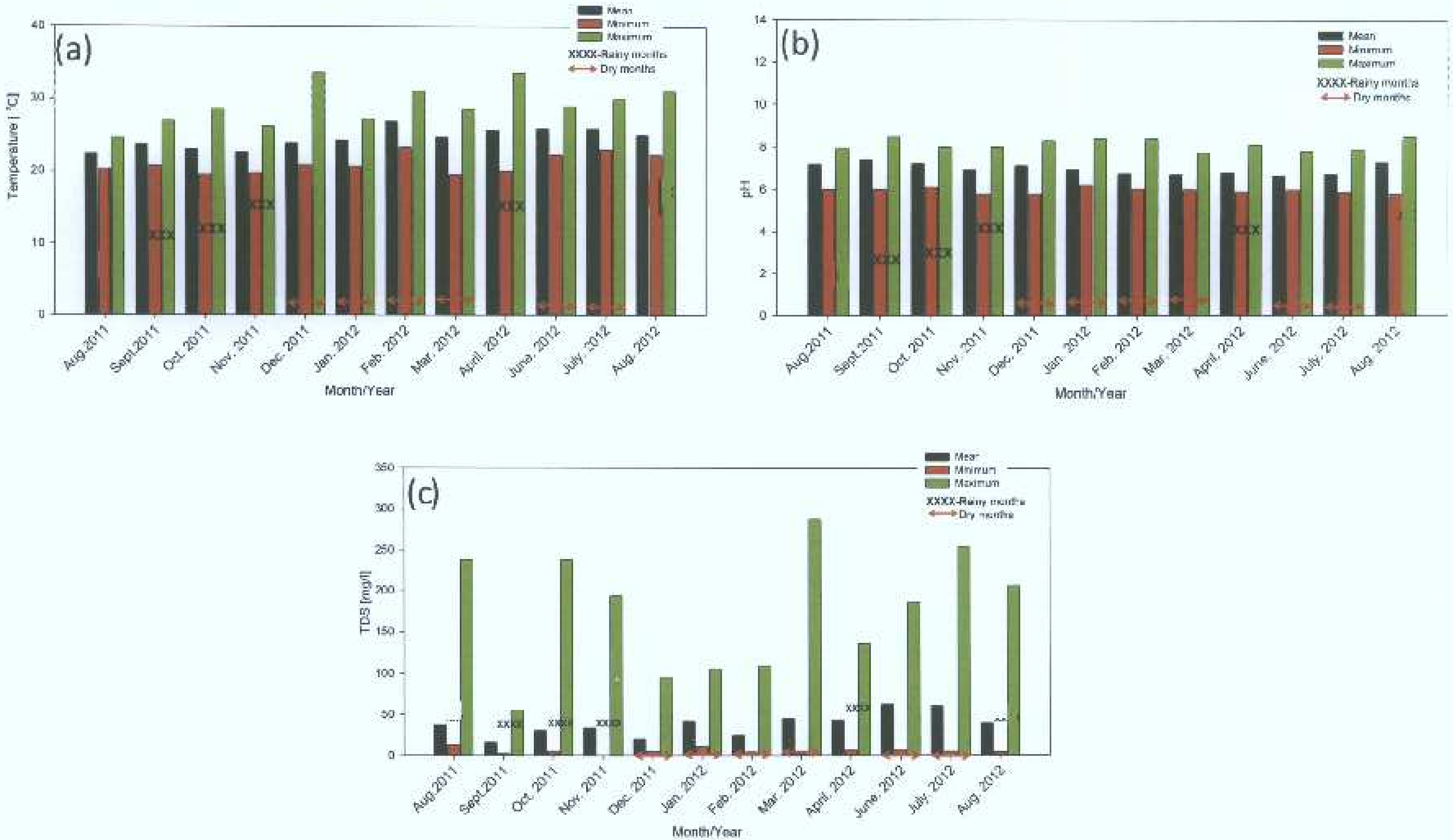


Figure 3.12: Physico-chemical parameters of HRW in Makondo-Masaka, Uganda a-temperature, b-pH and c-TDS

3.2.3 *Microbial quality of raw and SODIS treated HRW*

The total number of systems enrolled in the study was 8 catchment ponds, 11 concrete tanks, 20 metallic tanks and 11 plastic tanks. However, the general number of systems sampled each month varied depending on the availability of HRW in the systems. The number of systems studied is described in Figure 3.13. The dry season was characterized by a lower number of both raw and SODIS treated HRW compared to a rainy season since a number of HRW systems had no water in a dry season, especially towards the end. In the 12 months of the study, a total of 588 samples of raw HRW with their respective number of SODIS treated water was expected. However, only 462 and 459 samples of raw HRW and SODIS treated HRW respectively, were accessed. The remaining 21.4% and 21.9% of raw and treated HRW systems respectively, were not sampled mainly because of systems being empty with no HRW in the dry season. In some cases it was because of owners of the systems being unavailable on the days of sampling as they would be working in the fields. For SODIS treated water, some households would be visited after they had used/consumed all the SODIS exposed water.

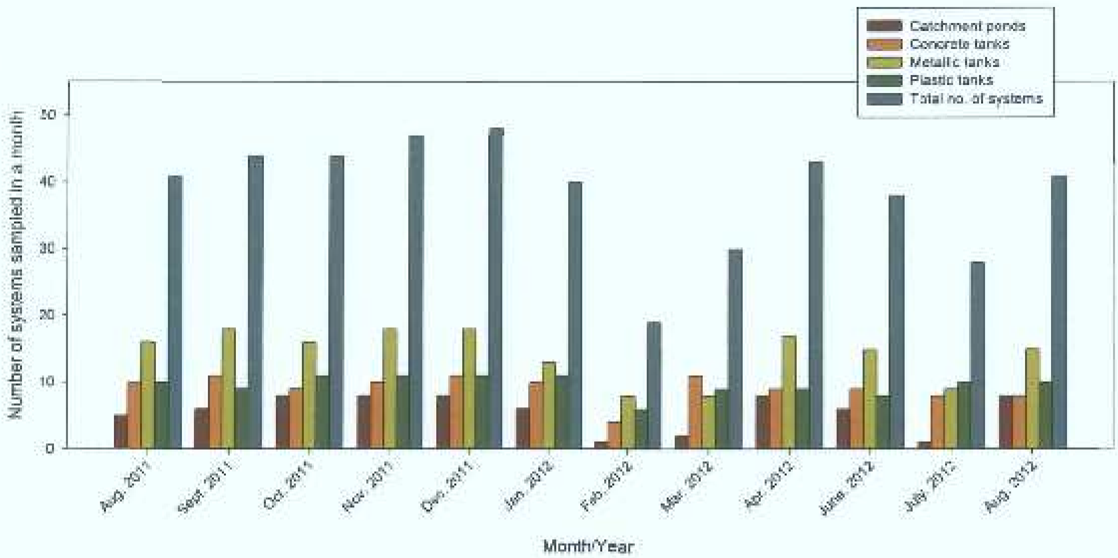


Figure 3.13: Number of HRW systems sampled

Catchment ponds and metallic tanks showed the widest variation of samples taken in a dry season due to the fact that many of catchment ponds were leaking and therefore were emptying faster than other systems. Similarly for catchment ponds, a lower percentage of metallic tanks were sampled in a dry season compared to a rainy season mainly because many of the metallic tanks were of very low volume with a small catchment, yet they were used by larger family units. Therefore these could not store water for a long time after rains. The microbiological quality of the harvested rainwater was evaluated by monitoring the presence of *E. coli* and faecal enterococci before and after SODIS. The presence of *Clostriium perfringens* was monitored from August 2011 to February 2012. None of the systems showed the presence of this bacterium.

3.2.3.1 Quality of HRW using *E. coli* as an indicator organism

The percentage of systems with potable water, using *E. coli* as an indicator organism, are described in Figure 3.14. The percentage of potable (uncontaminated) samples varied among the different systems. On a monthly basis, a lower percentage of catchment ponds were generally safer than other systems. The percentage of catchment ponds with potable water based on *E. coli* ranged from 0% to 30%. That is in some months, none of the catchment ponds sampled had potable water. For example in August 2011, March 2012, April 2012, July 2012, all the catchment ponds studied had *E. coli* and therefore all had unsafe drinking water according to WHO (2011) and UNBS (2009).

Although other systems showed relatively high percentages of potable HRW systems, 0% to 50% of concrete tanks showed potable water while 7 to 87% and 30-82% of metallic and plastic tanks, respectively, had potable systems.

The proportions (percentages) of HRW systems with potable water were generally lower during the rainy months than during the dry months

Following SODIS, the percentage of potable systems improved as described in Figure 3.16 The percentage of potable systems however, did not significantly ($p<0.05$) vary among the different systems 20-100% in catchment ponds, 50-90% in concrete systems, 67-100% in metallic tanks and 70-100% in plastic tanks. The detailed variation of *E.coli* contamination levels is shown in Appendix 9: *E. coli* contamination levels (CFU/100ml) in raw HRW systems and SODIS treated water during the different months of the year.

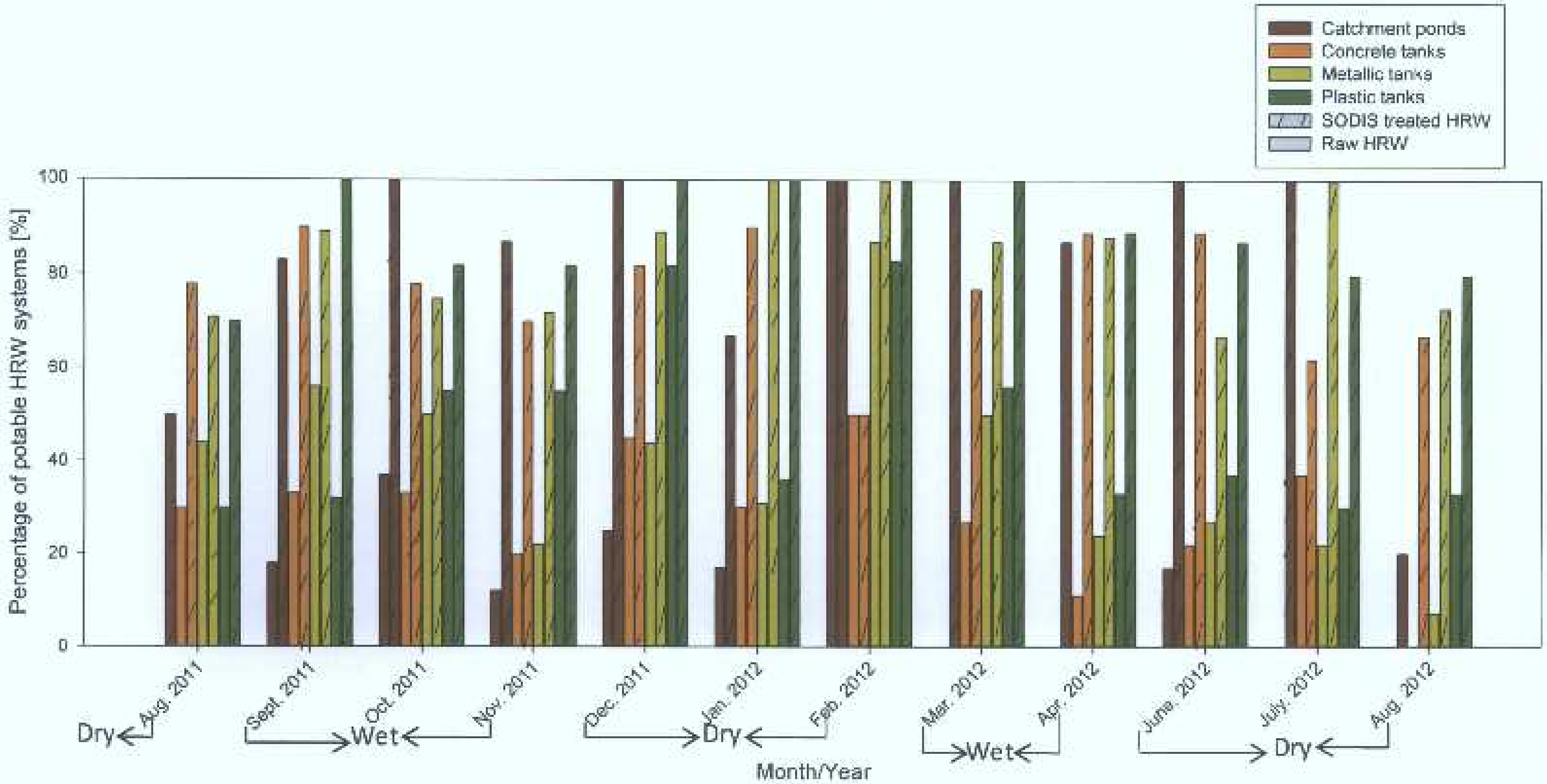


Figure 3.14: Percentage of potable HRW systems based on *E. coli* (note: no data collected in May)

3.2.3.2 Quality of HRW using faecal enterococci as indicator organism

The percentage of systems with potable water using faecal enterococci as an indicator organism, are described inFigure 3.15 Like *E. coli*, the percentage of potable (un-contaminated) samples also varied among the different systems. On a monthly basis, a lower percentage of catchment ponds was generally safer than other systems. The percentage of catchment ponds with potable water based on faecal enterococci ranged from 0% to 33%. In some months, none of the catchment ponds sampled had potable water. For example all the catchment ponds studied in August 2011 (5), December 2011 (8), Feb 2012 (1), March 2012 (2) and July 2012 (1) grew faecal enterococci and therefore all had unsafe drinking water according to WHO (2011) and (UNBS, 2009). In other systems, the percentage of potable systems were in ranges of 0-67, 8-75 and 9-67 in concrete, metallic and plastic tanks, respectively.

Generally, the proportions (percentages) of HRW systems with potable water were lower during the rainy months than during the dry months. The percentage of HRW systems with potable water generally improved after SODIS treatment as described in Figure 3.15. However, this percentage did not generally vary among the different systems. Overall, it generally ranged from 67% to 100%, i.e from 75-100%, 70-100%, 67-100% and 80-100% in catchment ponds, concrete, metallic and plastic tanks, respectively. Compared to *E. coli*, using faecal enterococci as a marker of contamination, there was higher percentage of HRW systems with potable water after SODIS treatment. The details of faecal enterococci contamination among the different systems and months is shown in Appendix 10: Faecal enterococci contamination levels in CFU/100ml in raw HRW systems and the SODIS treatment efficiencies during the different months in the year

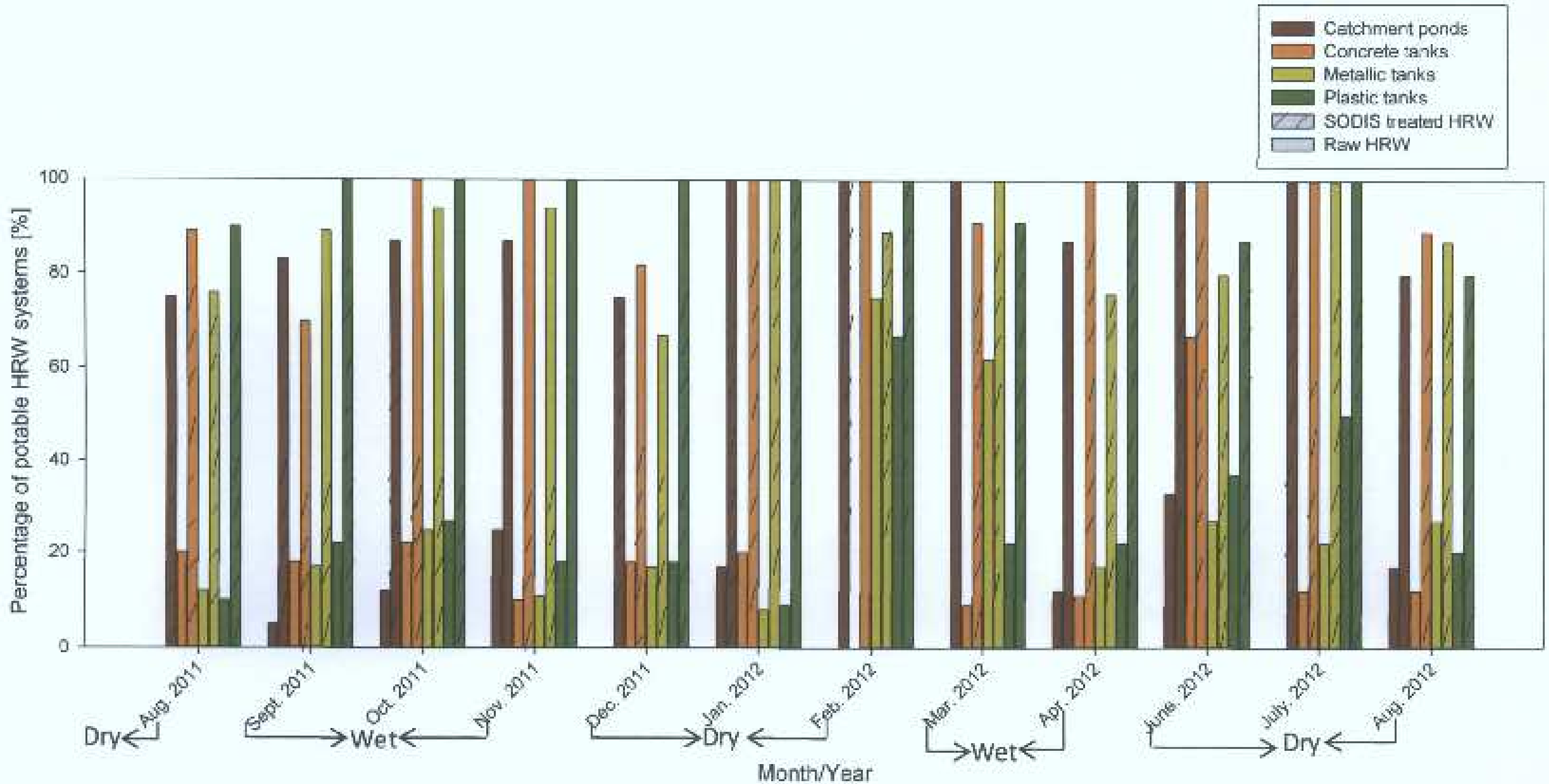


Figure 3.15: Percentage of potable HRW systems based on faecal enterococci

3.2.3.3 SODIS Treatment efficiency

To compare the effectiveness of SODIS in the different months, its treatment efficiency for each month was calculated as the total number of samples effectively treated divided by the total number of samples taken in a month multiplied by 100 as summarised in the formula presented below.

$$\text{Treatment efficiency [\%]} = \left(\frac{\text{No. of samples treated to zero cfu in a month}}{\text{Total no. of samples taken in a month}} \right) \mathbf{X}\ 100$$

Of the 462 raw water HRW samples, 409 samples (88.5%) were unsafe for drinking without any treatment (according to WHO (2011) and UNBS (2009) standard. That is *E. coli* or faecal enterococci were detected. Based on *E. coli* as the microbial quality indicator, only 132 (28.6%) met safe water standards of zero cfu/100ml, 248 (53.7%) samples were in a range of 1-100cfu/100ml and the rest were above 100CFU/100ml.

Based on faecal enterococci, only 84 (18.1%) samples were safe, 279 (60.4%) had a range of 1-100cfu/100ml and the rest were above the 100cfu/100ml. Following SODIS the minimum treatment efficiency was 61.2% using *E. coli* as the indicator organisms and was 78.9% when faecal enterococci were used as indicators (Figure 3.16). The maximum treatment efficiency was seen in January, February and July – all dry months. Generally, both faecal enterococci and *E. coli* were lower during the dry months than during the rainy months. Based on *E. coli* as indicator organism, treatment efficiency ranged between 71.0% and 86.5% during the rainy months while during the dry months, it ranged from 61.2% to 100%. For example during Feb 2012 (dry month), all the samples that were previously contaminated were *E. coli* free (100% treatment efficiency). Although, August 2011 and August 2012 were dry months, they showed the lowest treatment efficiency for *E. coli*, that is 61% and 64%, respectively.

Compared to *E. coli*, faecal enterococci were more often absent after treatment irrespective of the season. Using faecal enterococci as a marker, more samples were safe for drinking after treatment compared to water standards for *E. coli*.The variation of potable systems before and after treatment in different months is detailed in Appendix 11: Percentage of raw and SODIS treated HRW samples contaminated with *E. coli* according to different systems during the different months of the study and Appendix 12: Percentage of raw and SODIS treated HRW samples contaminated with faecal enterococci according to different systems

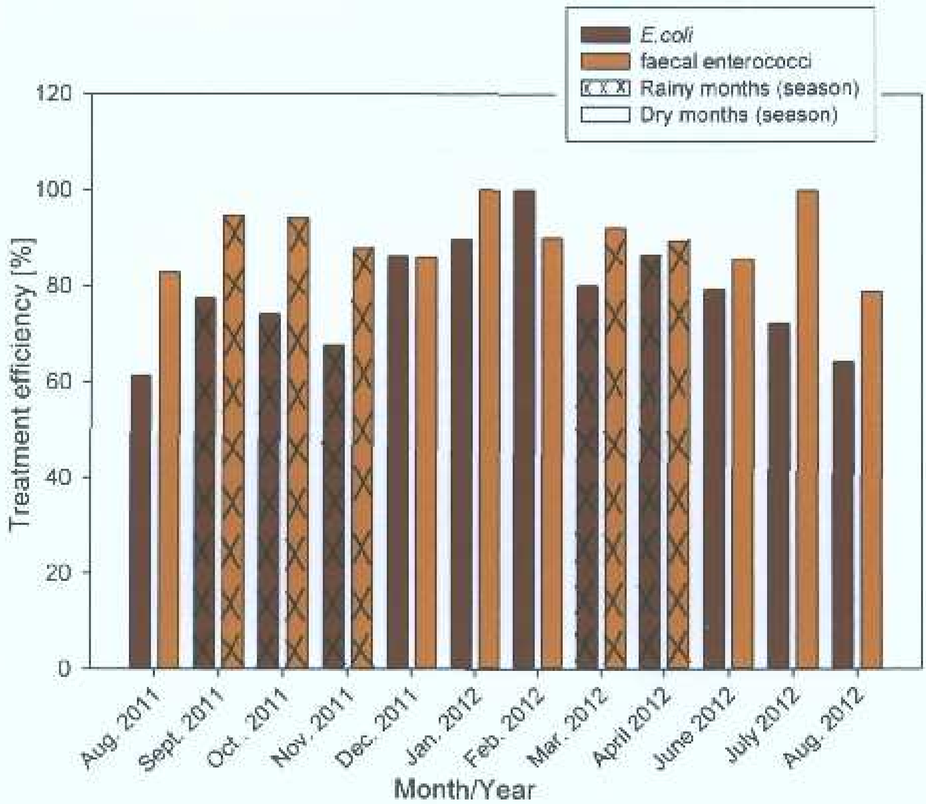


Figure 3.16: Treatment efficiency (% of effectively treated water samples) of HRW using SODIS based on *E. coli* and faecal enterococci as bacterial indicators.

3.2.4 *Rainfall and microbiological parameters of raw HRW*

Generally there were increased levels of contamination of both *E. coli* and faecal enterococci with increased amount of rainfall received in a month (Figure 3.17). For example, September 2011 received higher amounts of rainfall than August 2011 and the same trend of both median *E. coli* and faecal enterococci levels were observed. That is September 2011 showed higher median levels of both *E. coli* and faecal enterococci than August 2011. June 2012 and July 2012 showed the least amount of monthly total rainfall in addition to the lowest median levels of *E. coli* and faecal enterococci.

To ascertain if there was a relationship between rainfall and the contamination levels observed, a bivariate Pearson's correlation between median microbiological values and the monthly total rainfall was performed. The median number of *E. coli* showed no correlation with monthly total rainfall (R^2 =0.15; p=0.86). The weak correlation between rainfall and *E. coli* would suggest that rainfall amount is not the only contributing factor to the observed contamination levels

Like median *E. coli*, the median numbers of faecal enterococci also showed no correlation with monthly total rainfall (R^2 =0.27; p=0.389).

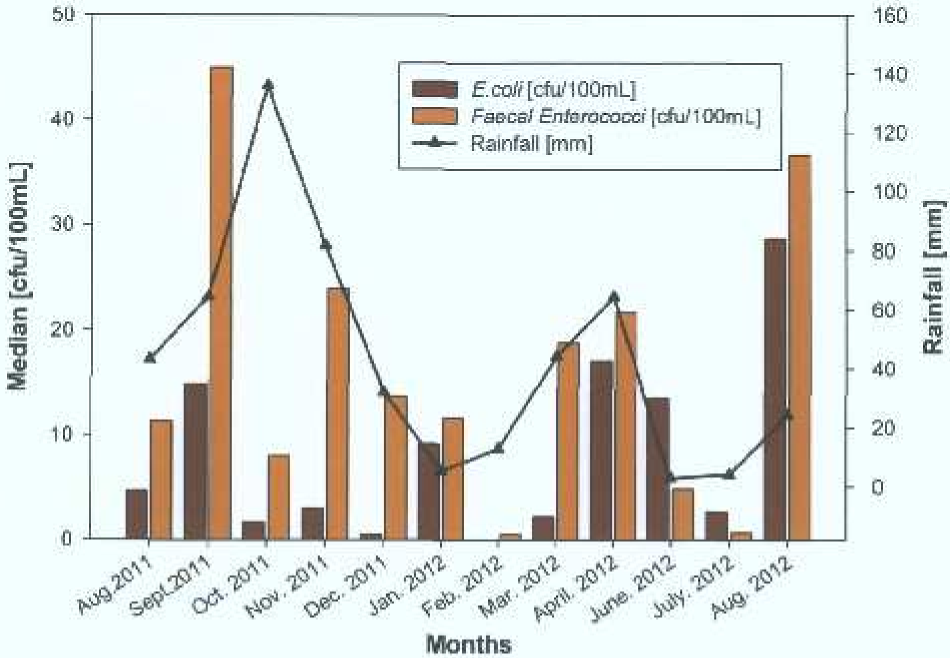


Figure 3.17: Graph showing monthly total rainfall and median levels of faecal enterococci and *E. coli* [cfu/100ml]

3.2.5 *Sanitary risk score of the HRW systems*

The sanitary risk score of the harvested rainwater systems was determined according to the WHO method described in section 2.4.6.1. The sanitary factors studied are listed in Table 3.9.

Table 3.9: Sanitary factors that were studied

Presence of birds or roaming animals
Presence of overhanging vegetation
Presence of pit latrine close to HRW system
Dirt or blockage of gutter
Leaking or defective tap
Manual abstraction of water from the storage tank
Presence of entry points/linkages (poor closing of the system)
Poor drainage of water collection area
Communal use/sharing of a system
Lack of cleaning/first rain flush out of the system

Generally, the sanitary conditions of most of the rainwater harvesting systems were not good. As shown in Figure 3.18 the distribution of sanitary risk scores of the rainwater harvesting revealed that 43% and 41% of HRW systems had medium and high sanitary risk score levels, respectively. Only 14% were at low risk, however, only 2% were found to be at high risk.

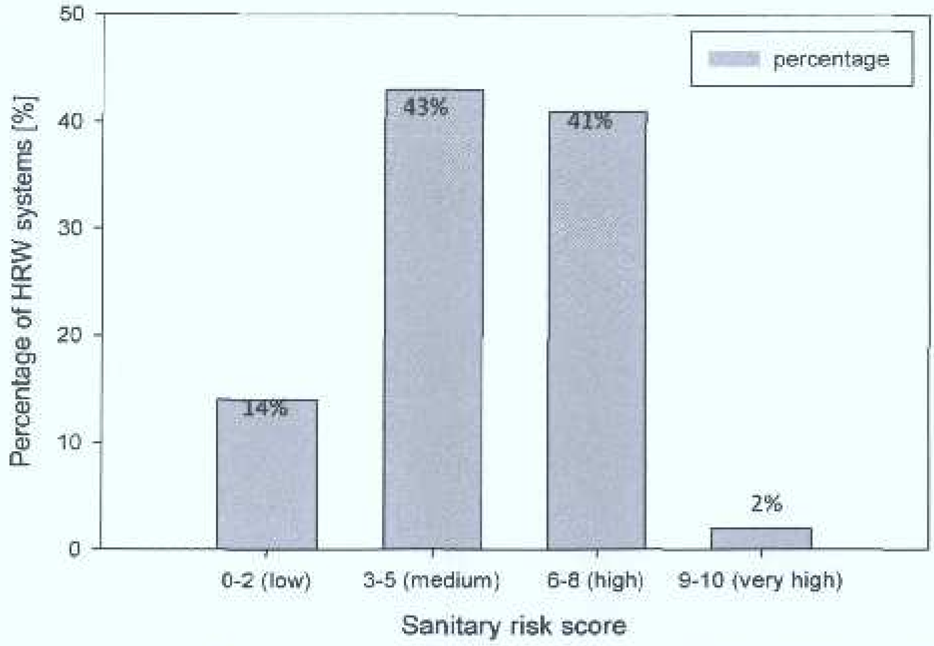


Figure 3.18: Distribution of sanitary risk scores of the HRW systems sampled in Makondo-Masaka Uganda

3.2.6 *An investigation of the influence of social and environmental conditions on the HRW quality*

It was of interest to investigate the influence of a variety of factors on the quality of the HRW. The factors included information gathered from a survey, which was conducted as described in section 2.3 together with other environmental conditions which were recorded every time a sample of HRW was collected. The factors investigated and their percentage occurrences are listed in Table 3.10. The influence of these factors on the water quality was investigated using TREE analysis as described in section 2.6. TREE analysis was conducted separately for *E. coli* and faecal enterococci. Initially all factors were included to generate a TREE diagram. Then the most significant factor was removed from the analysis to generate a further model and so on until the most significant factors influencing the water quality were identified.

Table 3.10: Characteristics of 462 households (462 respective systems) included in the study

Variable	Characteristics	No. (% composition)
Design	Below ground	86 (18.6)
	Above ground	376 (81.4%)
Type of HRW system material	Catchment	63 (13.6%)
	Concrete	110 (23.8%)
	Metallic	173 (37.4%)
	Plastic	116 (25.1%)
Dirty or blockage of gutter	Clean	23 (5.0%)
	Dirty	439 (95.0%)
Condition of drainage of water collection area	Good	217 (47.0%)
	Poor	245 (53.0%)
Volume remaining in a system	≤1/4	150 (32.5%)
	>1/4-1/2	187(40.5%)
	>1/2	125 (27.1%)
Size of household using HRW system	≤6	181 (39.2%)
	>6 and sharing	281(60.8%)
Presence of birds or roaming animals	None	47 (10.2%)
	Animals or birds	415 (89.8%)
Rainfall amount received in a month	2.9-12.9mm	126 (27.3%)
	>12.9-64.7mm	245(53.0%)
	>64.7-135.7mm	91 (19.7%)
No. of rainfall events in a month	4-11	126 (27.3%)
	>11-18	202 (43.7%)
	>18	134 (29.0%)
No. of days between the last two rainfall events	0-3 events	230 (49.8%)
	4-6	139 (30.1%)
	>6-30	93 (20.1%)

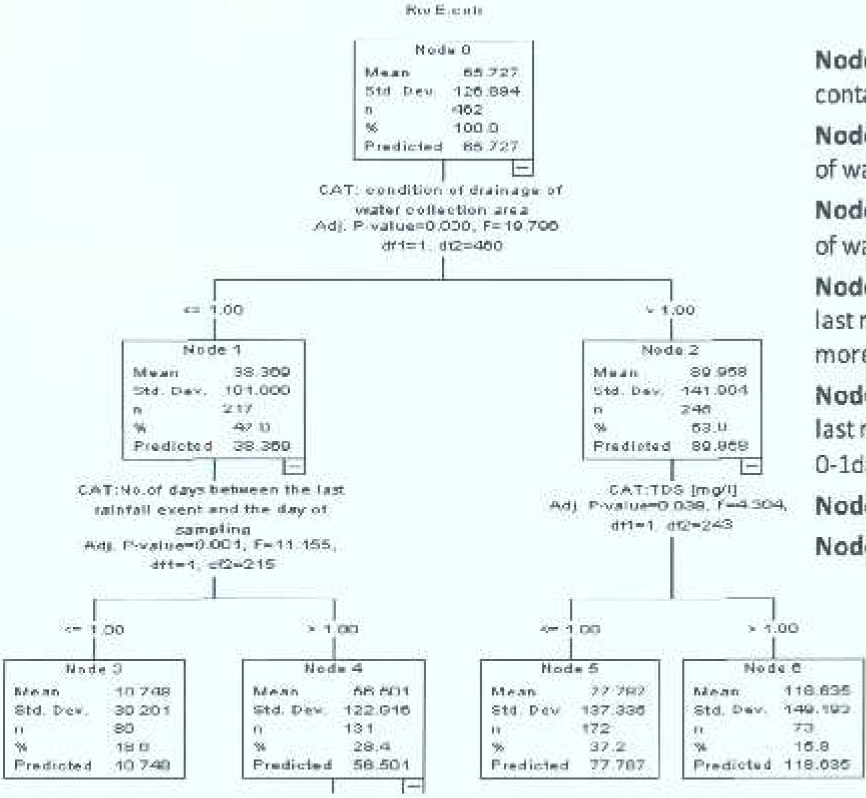
No. of days between last rainfall event and sampling	0 1-3 >3-28	170 (36.8%) 184 (39.8%) 108(23.4%)
Season	Wet Dry	288 (62.3%) 174 (37.7%)
Holiday/schooling time	Holiday School	132 (28.6%) 330 (71.4%)
Presence of overhanging vegetation	>4m ≤4m	172 (37.2%) 290 (62.7%)
Presence of pit latrine close to HRW system	>15m ≤15m	281 (60.8%) 181 (39.2%)
Mode of abstraction	Dipping using smaller containers (faulty tap) Tap	114(24.7%) 348 (75.3%)
Highest level of education of a family head	None Primary Secondary	47 (10.2%) 224 (48.5%) 192 (41.6%)
Cleaning/first rain flush out of the HRW system	No Yes	272 (58.9%) 190(41.1%)
Volume of the HRW system	500-3,000l >3000l-30,000L	317(68.8%) 145 (31.4%)
Temperature	19.5-24 24.1-33.6	243 (52.6%) 219 (47.4%)
pH	4.8-6.4 6.5-7.8 7.9	112 (24.2%) 267 (57.8%) 83 (18.0%)
TDS	0-50mg/l >50-287mg/l	356 (77.1) 106 (22.9%)

TDS-Total Dissolved Solids

Factors influencing the numbers of *E. coli* in the HRW

In developing an in-depth understanding of factors influencing the numbers of *E. coli* in HRW, tree analysis was used and six TREE diagrams were generated as follows;

Model 1: When all 22 variables were considered, the most significant factor ($p<0.001$) influencing the numbers of *E. coli* in the HRW was the condition of the water drainage collection area. In systems where the area below the tap was not draining well, the condition of this area was termed as poor while in those systems were the area was draining well, the water drainage area was said to be in good condition. Systems whose drainage of water collection areas were poor showed significantly ($P<0.05$) higher levels of *E. coli* (90±142) than those whose drainage systems were in good condition (38 ±101). The next most significant factor was the number of days between the last rainfall event and sampling (Figure 3.19).



Node 0: Average *E. coli* contamination

Node 1:≤1: Condition of drainage of water collection area is good.

Node2: >1 : Condition of drainage of water collection area is bad.

Node 3: ≤1: No. of days between last rainfall event and sampling is more than 1 day

Node 4: >1: No. of days between last rainfall event and sampling is 0-1day

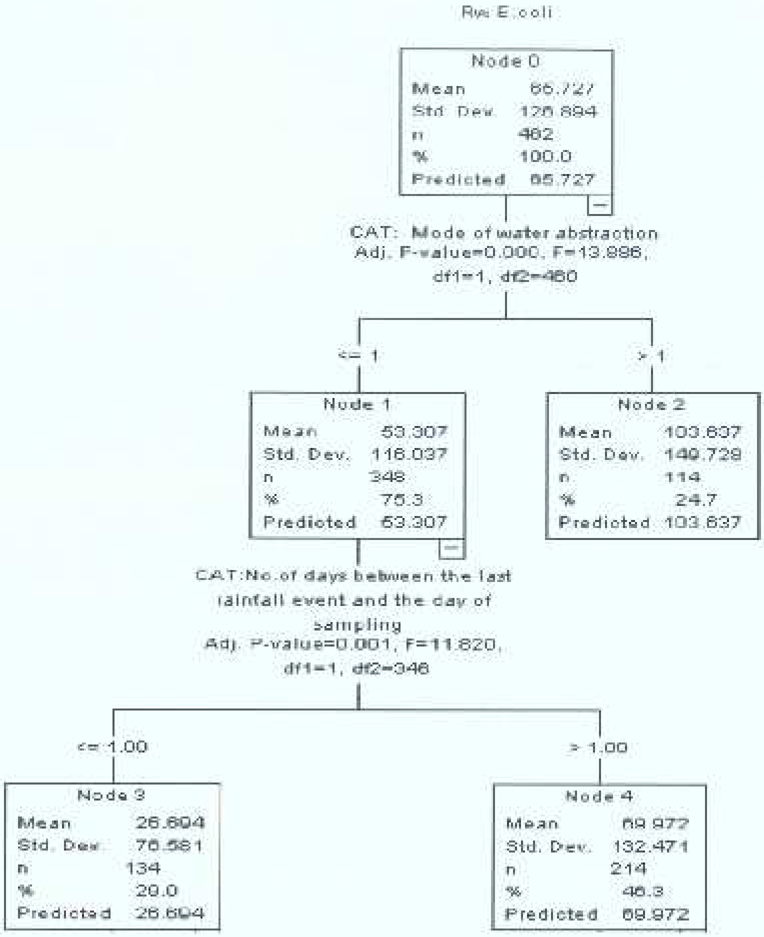
Node 5: ≤1: TDS is ≤50mg/l

Node6; >1: TDS is >50mg/l

Figure 3.19: Tree model 1 for *E. coli* contamination in HRW

HRW systems that were sampled during rains or after only one day of rains showed significantly ($p<0.05$) higher levels of *E. coli* (57 ± 123) than those that were sampled after more than a day of rains (11± 39). The TDS also had a significant ($p<0.05$) effect on the microbial quality of HRW. Systems with lower TDS had significantly lower levels of *E. coli*. HRW systems that had higher levels of beyond 50mg/L (node 6) had significantly higher levels of *E. coli* (119 ±149) than those with less than 50mg/L (node 5) (78 ±137).

Model 2: When the most significant factor in model 1 was excluded, the mode of water abstraction was found to be the most significant factor influencing the numbers of *E. coli* in the HRW (Figure 3.20). HRW systems which were abstracted using smaller containers due to faulty taps had significantly ($p<0.05$) higher levels of *E. coli* (104 ±150) than those that were abstracted using well-functioning taps (27±77).



Node 0: Average *E. coli* contamination

Node 1:≤1: water abstracted through tap (functional tap)

Node2: >1: water abstracted by small containers (tap faulty)

Node 3: ≤1:No. of days between last rainfall event and sampling is more than 1 day

Node 4: >1: No. of days between last rainfall event and sampling is 0-1day

Figure 3.20: Tree model 2 for *E. coli* contamination in HRW

The second significant factor was again the number of days between last rainfall event and the time of sampling which was also revealed by tree model 1. When the tap is functioning, the numbers of *E. coli* are influenced by the number of days between the last rainfall event and the time of sampling. HRW systems that were sampled during rains or after only one day of rains (node 4) had significantly ($p<0.05$) higher levels of *E. coli* (70 ± 132) than those that were sampled after more than a day of rains (11 ± 39).

MODEL 3: In tree model 3, which is presented in Figure 3.21 , the distance between the HRW system and vegetation was shown to be the most significant factor influencing the *E. coli* levels in HRW. Systems that were close to vegetation showed significantly ($p<0.05$) higher levels of *E. coli* contamination than those that were far away from vegetation. HRW systems that were a distance of 4m or less (node 2) had significantly ($p<0.05$) higher levels of *E. coli* (81 ± 136) than those that were more than 4m away (node 1) (40 ± 105). When the HRW systems were less than 4m, the levels of *E. coli* were influenced by TDS. Systems with lower levels of TDS had significantly low levels of *E.*

coli. HRW systems that had levels beyond 50mg/L (node 6) had significantly higher levels of *E. coli* (121 ±146) than those with less than 50mg/L (node 5) (69 ±131). When the HRW systems were more than 4m away or more (node 1) from vegetation, the numbers of *E. coli* were influenced by the number of days between the last rainfall event and the time of sampling. HRW systems that were sampled during rains or after only one day of rains (node 4) had significantly ($p<0.05$) higher levels of *E. coli* (56 ± 123) than those that were sampled after more than a day of rains (14± 55).

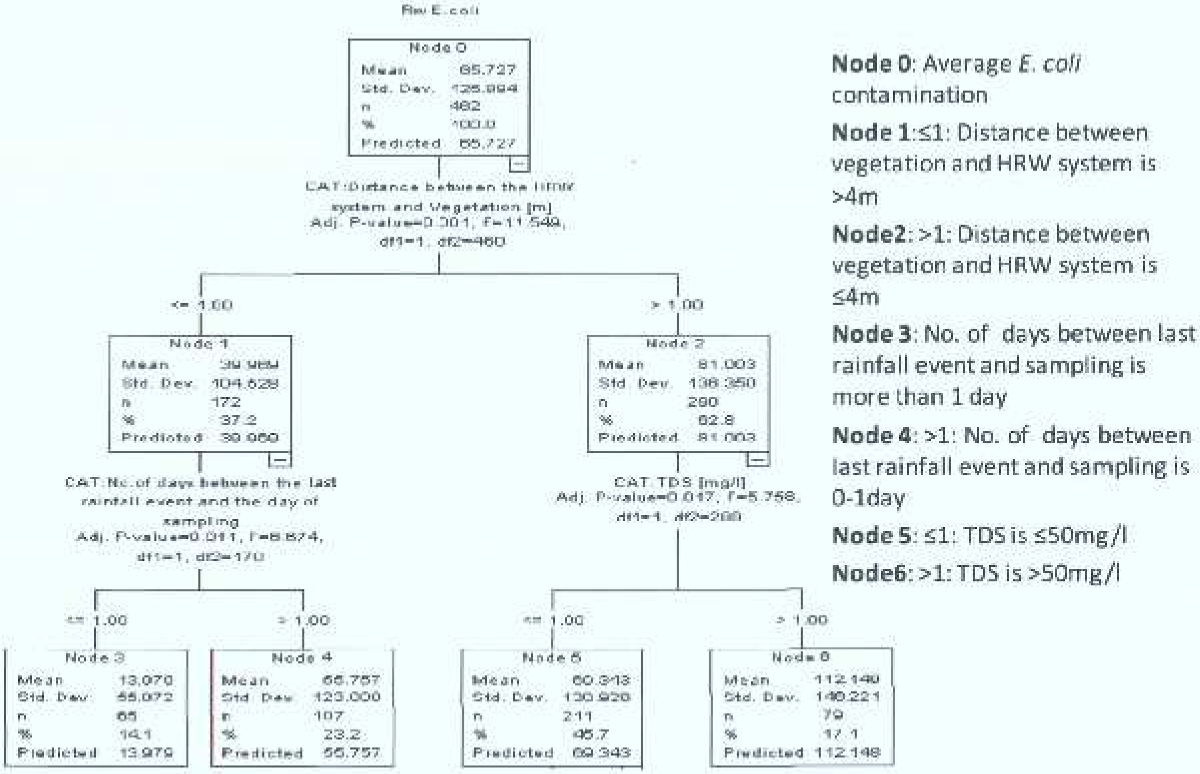
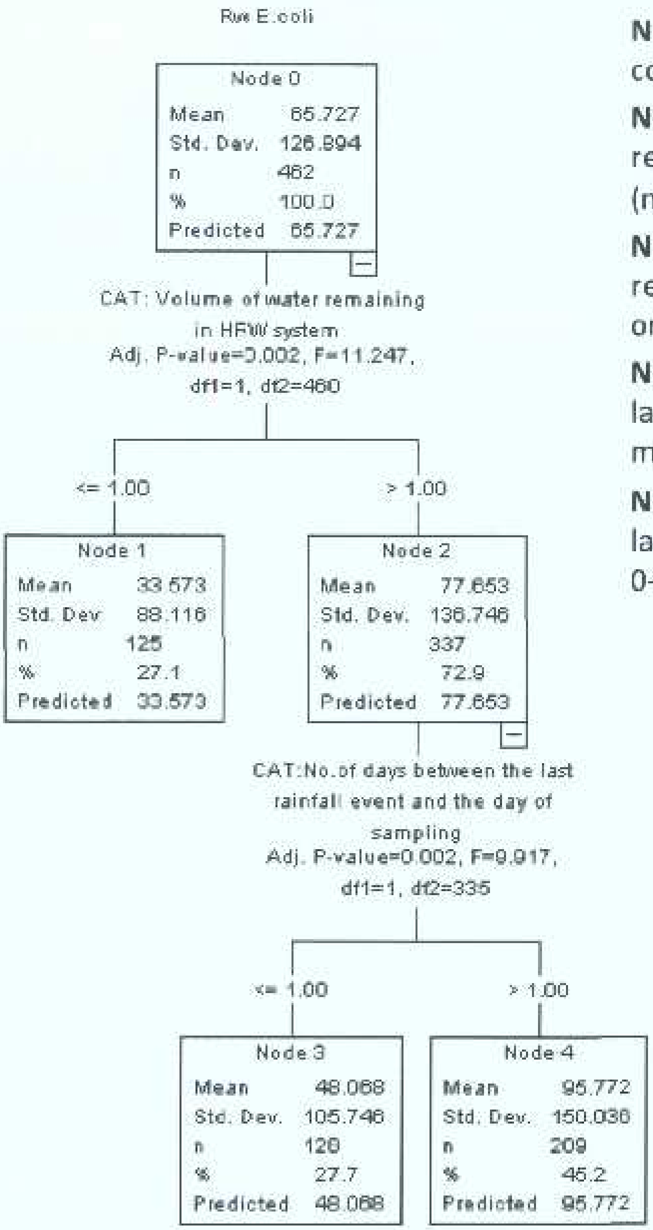


Figure 3.21: Tree model 3 for *E. coli* contamination in HRW

MODEL 4: In tree model 4, which is presented in Figure 3.22, the amount of water remaining in the tank on sampling was predicted as the most significant factor influencing *E. coli* levels in HRW systems. HRW systems that had less volume of water remaining had significantly higher levels of *E. coli* than those that were almost full. For example those HRW systems that were half full or less (node 2) had significantly ($p<0.05$) higher levels of *E. coli* (77± 136) than those which were more than half full (node 1) (34±88). The other significant factor predicted by this model was the number of days between the last rainfall event and the time of sampling. When the HRW systems were half full or less (node 2), the numbers of *E. coli* were influenced by the number of days between the last rainfall event and the time of sampling. HRW systems that were sampled during rains or after only one day of rains (node 4) showed significantly ($p<0.05$) higher levels of *E. coli* (96 ± 150) than those that were sampled after more than a day of rains (48 ± 106).



Node 0: Average *E. coli* contamination

Node 1:≤1: The volume of water remaining in a system is >0.5 (more than half full)

Node2: >1: The volume of water remaining in a system is ≤0.5 (less or equal to half full)

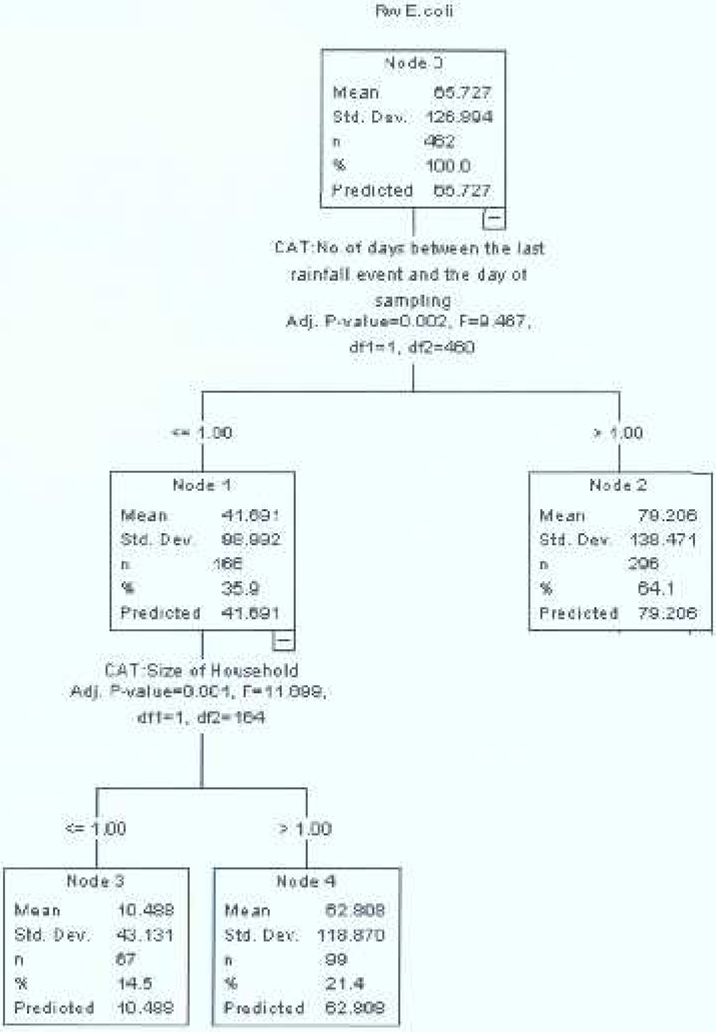
Node 3: ≤=1 No. of days between last rainfall event and sampling is more than 1 day

Node 4: >1: No. of days between last rainfall event and sampling is 0-1day

Figure 3.22: Tree model 4 for *E. coli* contamination in HRW

MODEL 5:

In model 5, the number of days between the last rainfall event and sampling day was shown to be the most significant factor (Figure 3.23). Other factors predicted were number of rain fall events in a month and the number of people using or sharing a system. HRW systems that were shared or used by larger households of more than 6 people (node 2) had significantly ($p<0.05$) higher levels of *E. coli* contamination (63±119) compared to those that were used by small households of 6 people or less without sharing between different households (node 1) (10±43).



Node 0: Average *E. coli* contamination

Node 1: ≤1: No. of days between last rainfall event and sampling is more than 1 day

Node 2: >1: No. of days between last rainfall event and sampling is 0-1day

Node 3: ≤1: No. of people in a household is ≤6

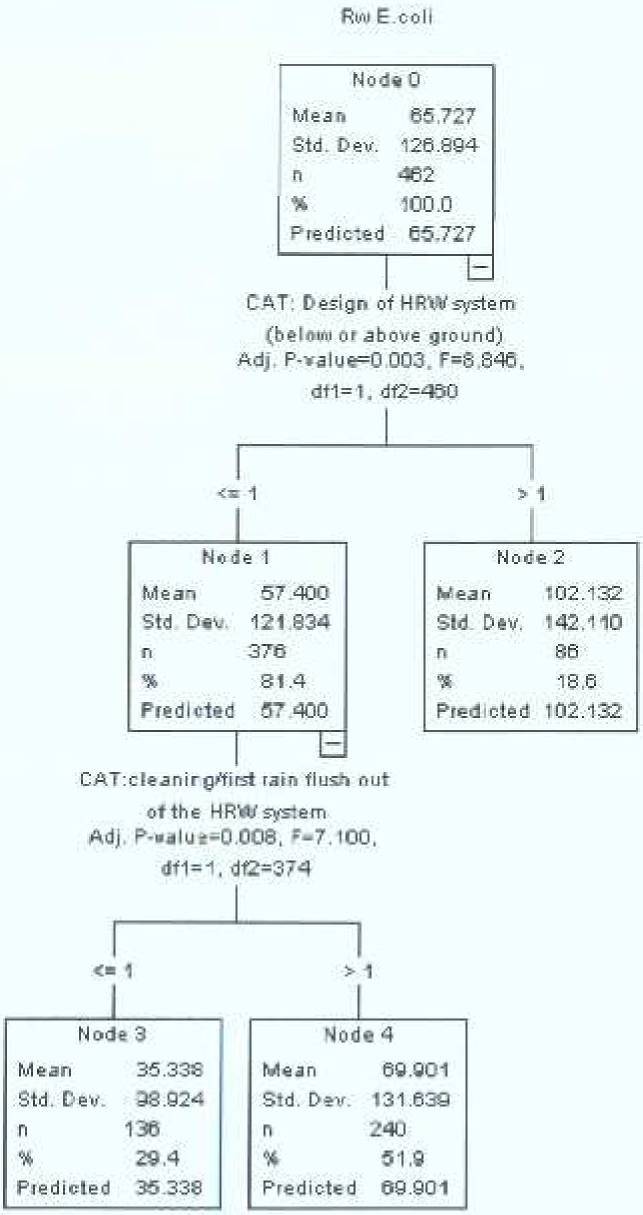
Node 4: >1: No. of people in a household using system is >6 or different households share a system

Figure 3.23: Tree model 5 for *E. coli* contamination in HRW

MODEL 6:

In tree model 6, which is presented (Figure 3.24), the design of the system, that is whether it was either below or above the ground was found to be the most significant factor. HRW systems which were designed in such a way that they were below the ground (node 2) had significantly ($p<0.05$) higher levels of *E. coli* (102±142) than those that were above the ground (node 1) (57±122). The practice of cleaning or flushing out the first rains was another factor significantly influencing *E. coli* levels in HRW. HRW systems which were reported to be neither cleaned before the rainy season nor flushed out after the first rainfall event (node 2) had significantly ($p<0.05$) higher levels of *E.*

coli (70 ±132) than those that were either cleaned before the rainy season or flushed out after first rainfall event (node 1).



Node 0: Average *E. coli* contamination

Node 1: ≤1: The HRW is above the ground

Node 2: >1: The HRW is below the ground

Node 3: ≤1: The HRW is either cleaned before first rains or first rain is flushed out

Node 4: >1: The HRW is neither cleaned nor first rains flushed out

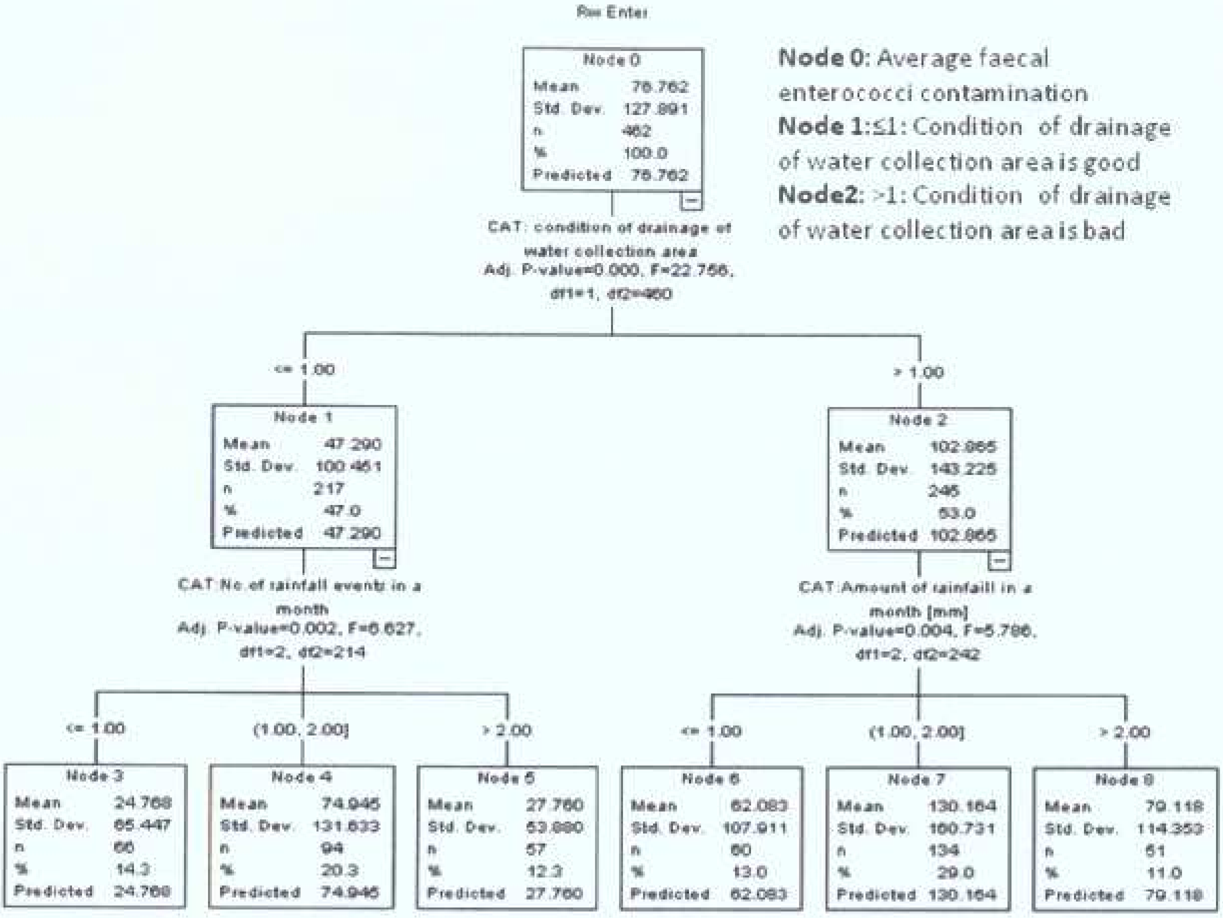
Figure 3.24: Tree model 6 for *E. coli* contamination in HRW

Factors influencing the numbers of faecal enterococci in the HRW

When TREE analysis was carried out to investigate the factors influencing the numbers of faecal enterococci, seven TREE models showed the most significant factors which are described as follows;

Model 1:

In this model (Figure 3.25), the condition of the drainage of water collection area was found to be the most significant factor influencing the levels of faecal enterococci. Like *E. coli,* HRW systems whose water collection areas were in poor condition (node 2) had significantly ($P<0.05$) higher levels of faecal enterococci (102±143) than those whose drainage systems were in good condition (node 1) (47±100). The next most significant factor was the number of rainfall events in a month. Systems that received rainfall 12-18 times (node 4) in a month had significantly ($p<0.05$) higher levels of faecal enterococci (75±132) than those which received less than 12 rainfall events, or more than 18 events (node 3 and node 5). The amount of rainfall in a month was another factor that was predicted to have a significant effect on the levels of faecal enterococci in model 1. HRW systems that received between 12.9 to 64.7mm in a month (node 7) had significantly ($p<0.05$) higher levels of faecal enterococci (130 ±161) than those which received less than 12.9mm, or more than 64.7mm (node 6 and node 8).



Node 3: ≤1: No. of rainfall events in a month is ≤ 11 times
Node 4: 1,2: No. of rainfall events in a month is between 11-18 times
Node 5: >2: No. of rainfall events in a month is >18 times
Node 6: ≤ 1: The total amount of rainfall in a month is ≤ 12.9
Node 7:1,2: The total amount of rainfall in a month is between 12.9 and 64.7mm
Node 8:>2: The total amount of rainfall in a month is > 64.7mm

Figure 3.25: Tree model 1 for faecal enterococci contamination in HRW

Model 2:

In tree model 2 (Figure 3.26), the amount of rainfall received in a month was predicted as the most significant factor influencing levels of faecal enterococci. The second factor which also showed a significant effect on faecal enterococci levels was the number of days between the last two rainfall events. The number of days between the last two rainfall events was computed as a measure for accumulation of waste on collection roofs. For systems that received rainfall after 7 or less days from a previous rainfall (node 5) had significantly ($p<0.05$) higher levels of faecal contamination (72±127) compared with those which received rainfall greaterthan 7days after previous rainfall (node 4) (23±127).

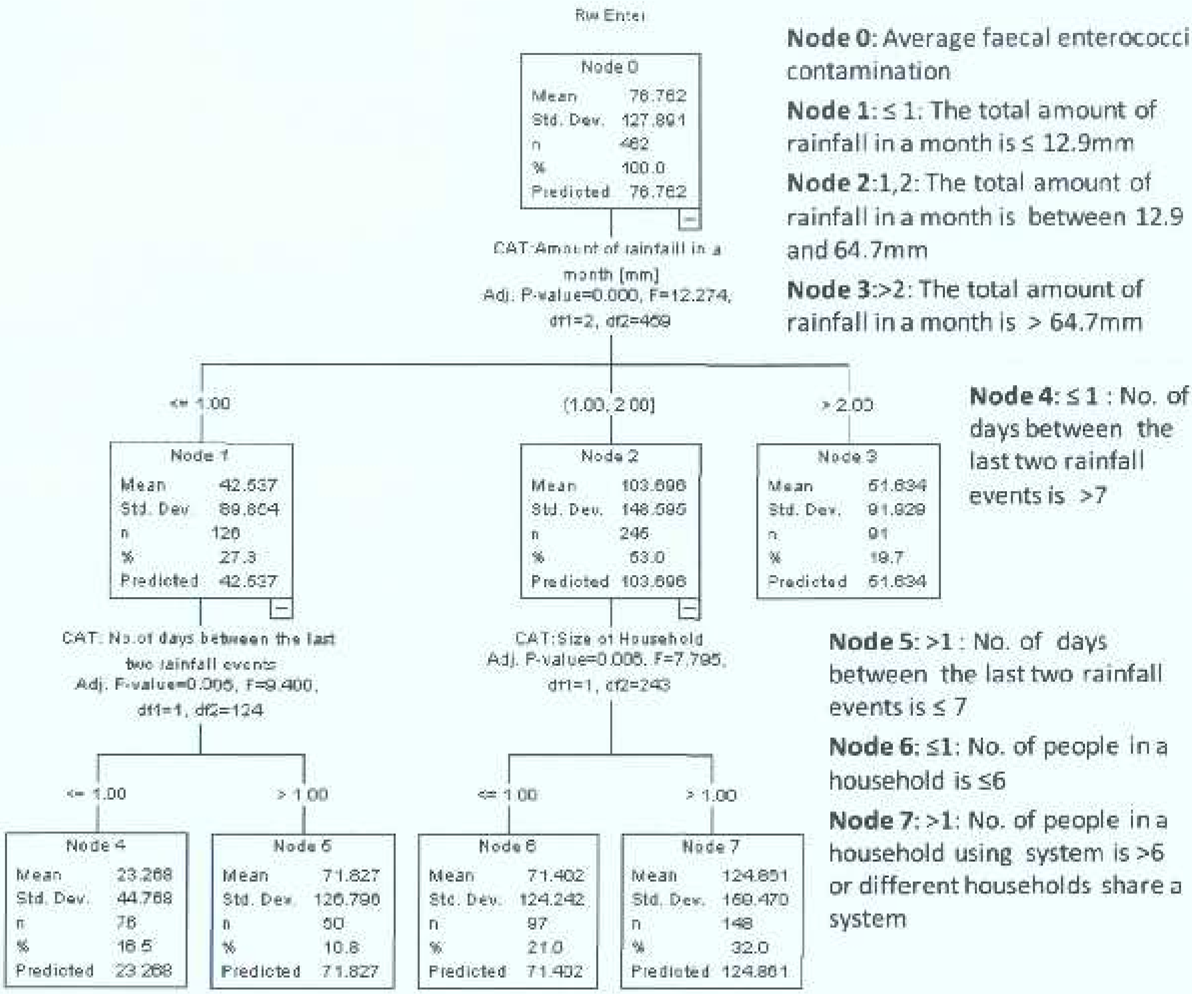
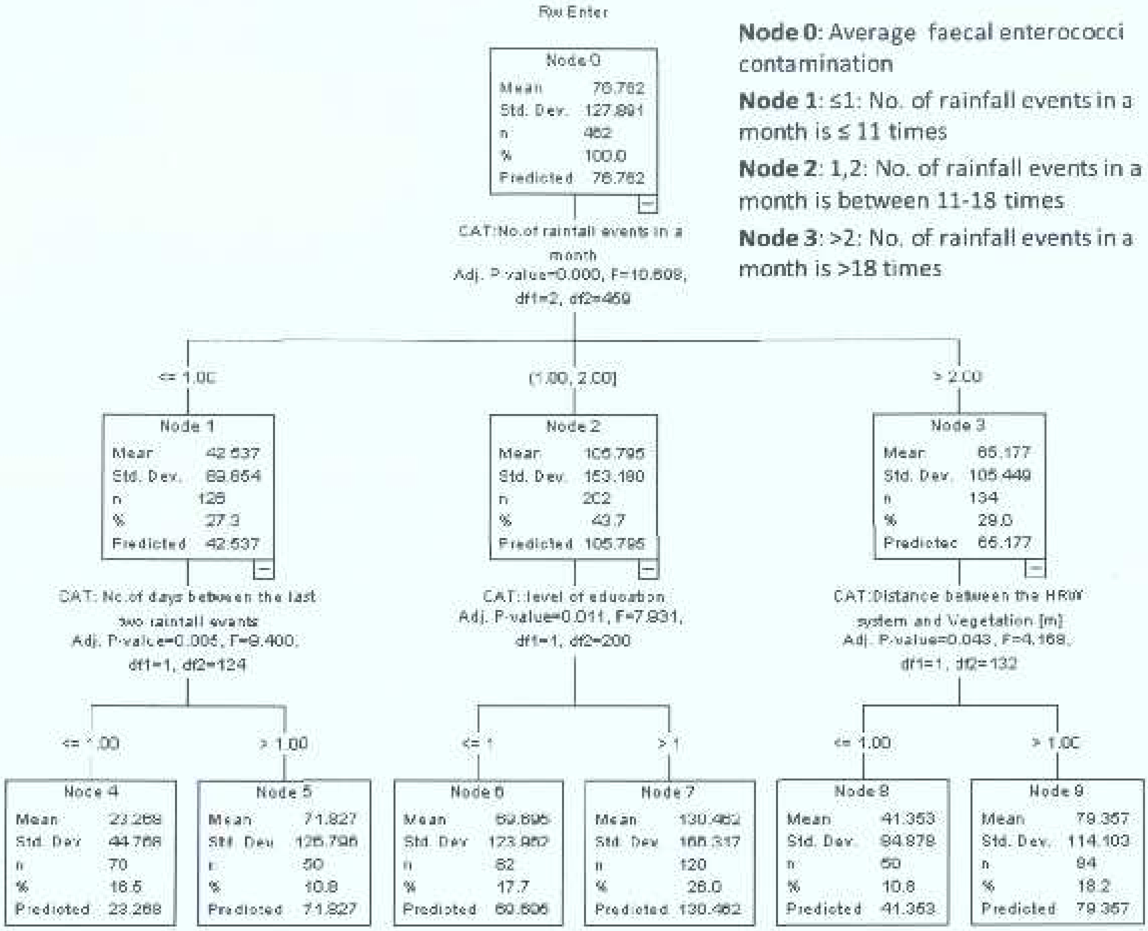


Figure 3.26: Tree model 2 for faecal enterococci contamination in HRW

The other factor which was predicted by model 2 was household size. HRW systems that were used by greater numbers of people or those that were shared between different households (node 7) had significantly ($p<0.0\%$) showed higher levels of faecal enterococci (124±159) than those that were used by a single household, or by fewer numbers of people (node 6) (71±124).

Model 3:

In this model, the number of rainfall events in a month was shown to be the most significant factor affecting the levels of faecal enterococci (Figure 3.27). The other significant factors which were predicted by this model were the days between the last two rainfall events.



Node 4: ≤ 1 : No. of days between the last two rainfall events is >7
Node 5: >1 : No. of days between the last two rainfall events is ≤ 7
Node 6: ≤ 1 : the highest level of education of family head is secondary
Node 7: >1 : the highest level of education of family head is either primary or none at all
Node 8: ≤1: Distance between vegetation and HRW system is >4m
Node 9: >1: Distance between vegetation and HRW system is ≤4m

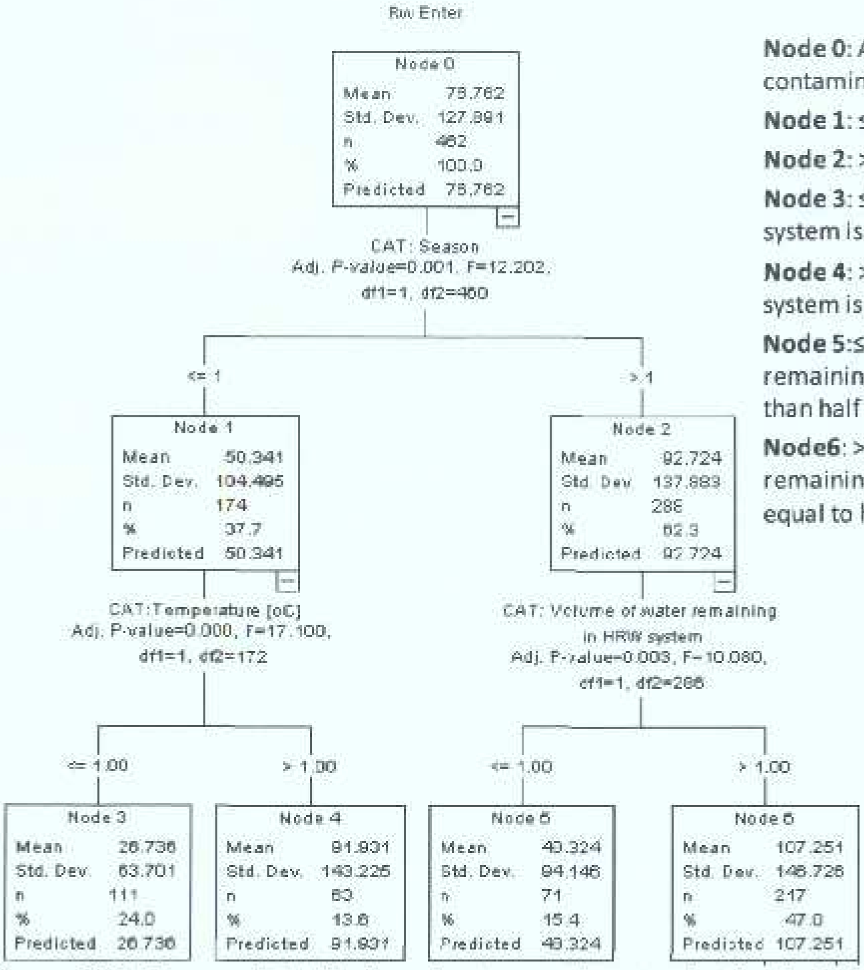
Figure 3.27: Tree model 3 for faecal enterococci contamination in HRW

Other factors that were predicted by this model were the level of education and the distance between HRW system and vegetation. When the number of rainfall events in a month was ≤11, the number of faecal enterococci was influenced by the number of days between the last two rainfall events. The other factor influencing faecal enterococci levels when the number of rainfall events in a month was between 11-18 was the size of the household. HRW systems which were owned by family heads with a primary level of education or no education at all (node 7) had significantly ($p<0.05$) higher levels of faecal enterococci (130±166) than those that were owned by family heads with a secondary level of education (node 6) (70±124). Like *E. coli*, faecal enterococci was also shown to be influenced by the distance between the HRW system and vegetation. When the number of rainfall events in a month was more than 18, systems that were 4m or less (node 9) from vegetation had significantly ($p<0.05$) higher levels of faecal enterococci (79±114) than those that were more than 4m away (node 8) (41±85).

Model 4:

In tree model 4 which is presented in Figure 3.28 season was found to be the most significant factor affecting the levels of faecal enterococci. Like *E. coli*, HRW systems that were sampled in the rainy season (node 2) had significantly ($p<0.05$) higher levels of faecal enterococci (93±138) than those that were sampled during a dry season (50±104). During the dry season, the levels of faecal enterococci were predicted to be significantly ($p<0.05$) influenced by temperature. HRW systems that had temperatures of ≤ 24°C (node 4) had significantly ($p<0.05$) higher levels of faecal enterococci (92±143) than those that had higher temperature of above 24°C (27±63).

Unlike in a dry season, the levels of faecal enterococci in a wet (rainy) season were found to be significantly ($p<0.05$) influenced by the volume of water remaining in the tank at the time of sampling. HRW systems that had less volume of water remaining significantly ($p<0.05$) had higher levels of faecal enterococci than those that were almost full. For example those HRW systems that were half full or less (node 6) had significantly ($p<0.05$) higher levels of faecal enterococci (107±147) than those which were more than half full (node 5) (48±94).



Node 0: Average faecal enterococci contamination

Node 1: ≤1: dry season

Node 2: >1:wet (rainy) season

Node 3: ≤1: The temperature of HRW system is >24°C

Node 4: >1:The temperature of HRW system is ≤ 24°C

Node 5:≤1: The volume of water remaining in a system is >0.5 (more than half full)

Node6: >1: The volume of water remaining in a system is ≤0.5 (less or equal to half full)

Figure 3.28: Tree model 4 for faecal enterococci contamination in HRW

Model 5

In tree model 5 which is presented in Figure 3.29, the number of days between the last two rainfall events was shown to be the most significant factor. When the number of days between last two rain fall events was ≤7, the number of fecal enterococci in HRW was influenced by the volume of water remaining is the tank. HRW systems that were half full or less (node 4) had significantly ($p<0.05$) higher levels of faecal enterococci (102±144) than those which were more than half full (node 3) (50±99).

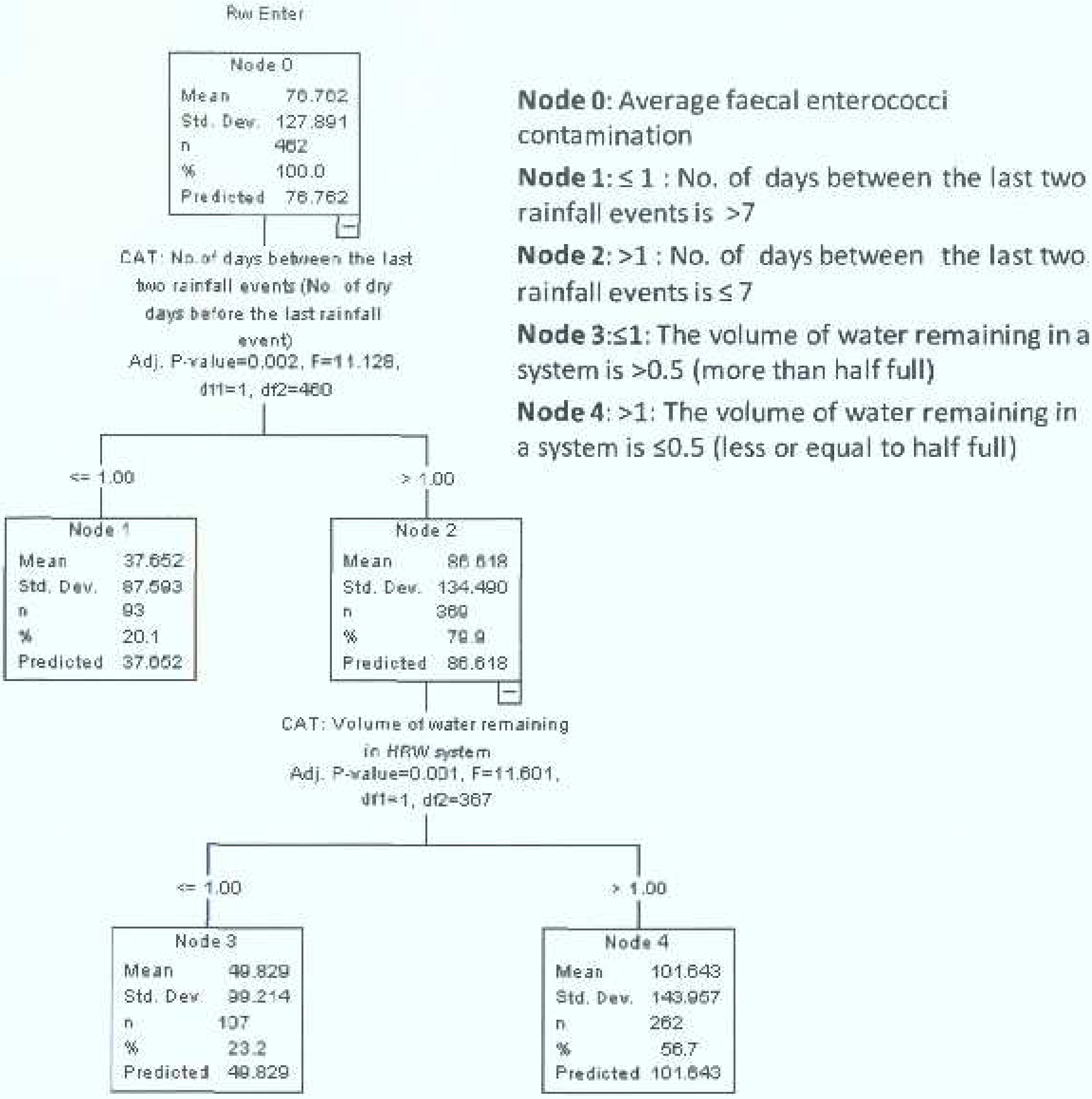


Figure 3.29: Tree model 5 for faecal enterococci contamination in HRW

Model 6:

In tree model 6 which is presented in Figure 3.30, the distance between the HRW system and vegetation was predicted as the most significant factor influencing the levels of faecal enterococci. HRW systems which were ≤4m away from vegetation (node 2) had significantly ($p<0.05$) higher levels of faecal enterococci (Figure 3.30) than those more than 4m away. When a system was within a distance of ≤4m, its levels were also significantly ($p<0.05$) affected by the level of education of the family head. HRW systems which were owned by family heads with a primary level of education or no education at all (node 6) had significantly ($p<0.05$) higher levels of faecal enterococci

(108±141) than those that were owned by family heads with a secondary level of education (node 6) (59±112).

The number of faecal enterococci in systems located more than 4m away from vegetation was also predicted to be significantly influenced by the volume of water remaining in a tank as described in Figure 3.30 below.

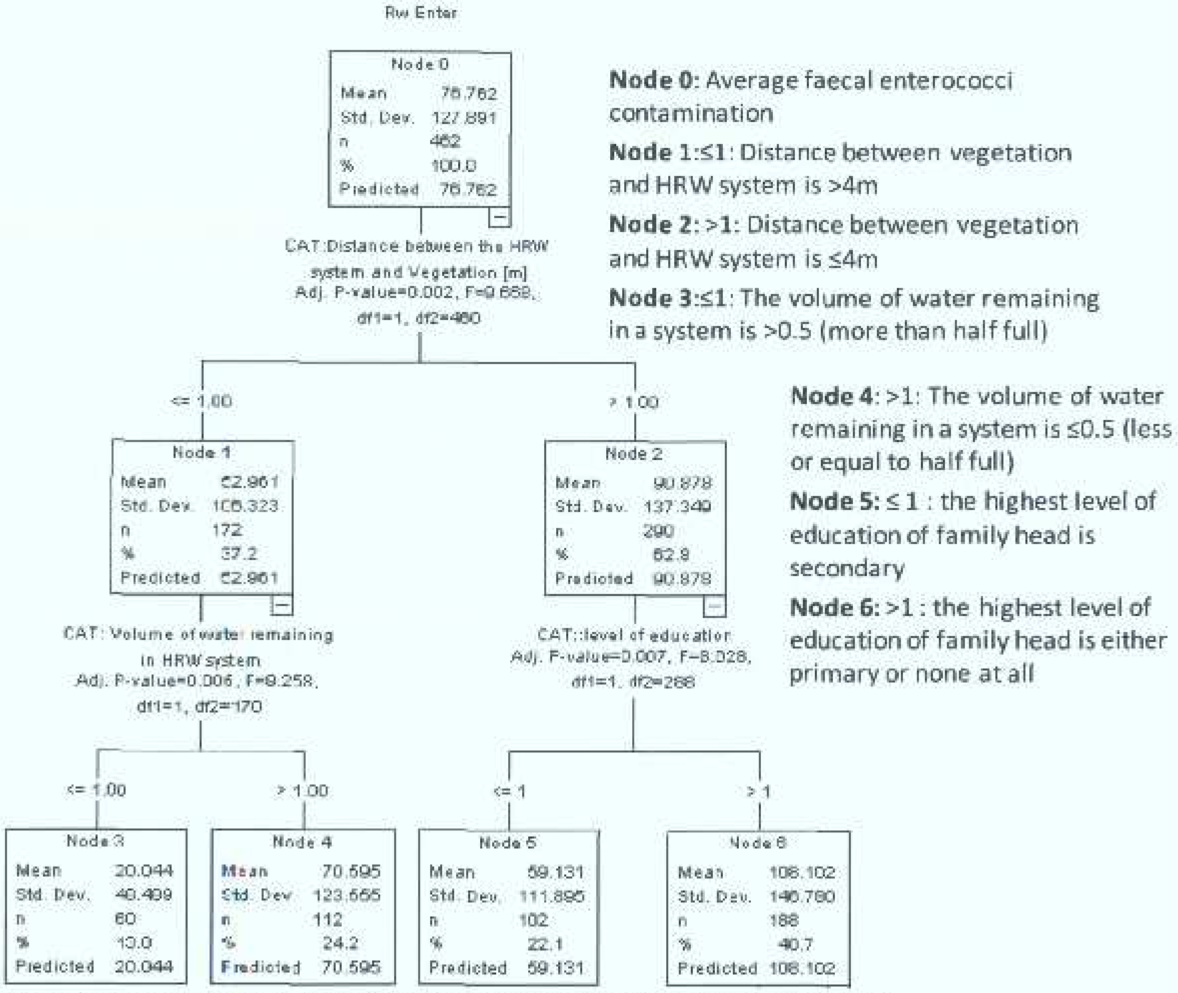


Figure 3.30: Tree model 6 for faecal enterococci contamination in HRW

Model 7:

The findings of model 7 are presented in Figure 3. 31 below in which the volume of water remaining in a system was shown to be the most significant factor. HRW systems that were half way or less full (node 2) had significantly ($p<0.05$) higher levels of faecal enterococci (89±137) than those which were more than half full (node 3) (45±93).

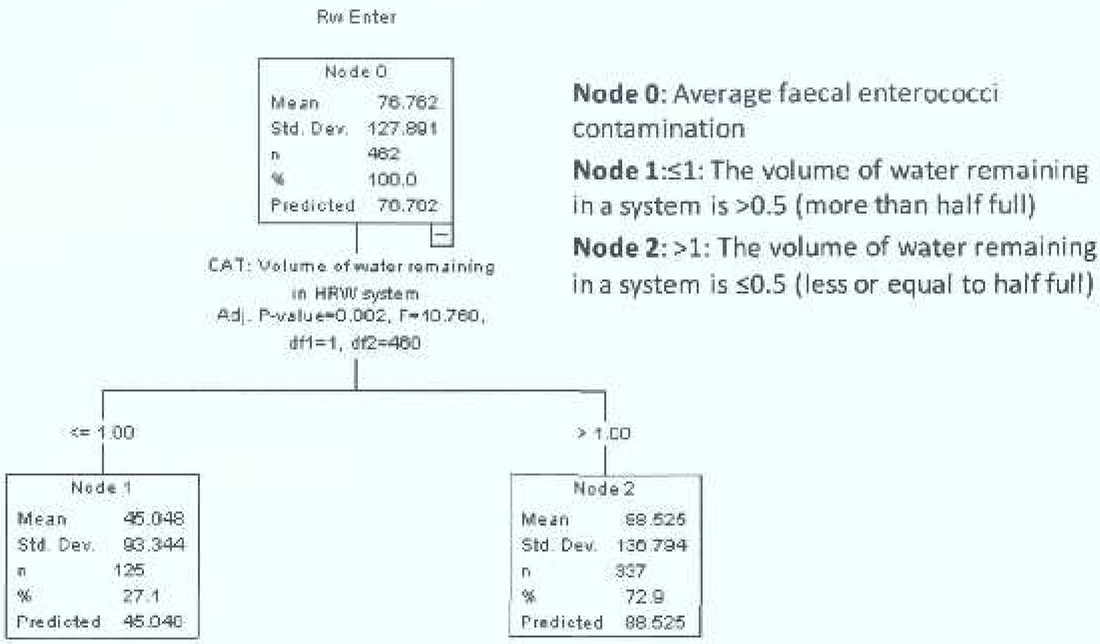


Figure 3. 31: Tree analysis result 7 for faecal enterococci contamination in HRW

Summary of factors significantly affecting the microbial quality of raw HRW

The most significant factors influencing the number of indicator organisms in the HRW are summarized in Table 3.11. The factors are listed in the order of significance. The most significant factor for both indicator organisms was the condition of drainage of the water collection area. The other factors differed for the two indicators.

Table 3.11: Summary of factors influencing the levels of *E. coli* and Faecal enterococci in HRW

E. coli	Faecal enterococci
Condition of drainage of water collection area	Condition of drainage of water collection area
Mode of water abstraction	Amount of rainfall in a month
Distance between HRW system and vegetation	The number of rainfall events in a month
Volume of water remaining	Season
Number of days between last rainfall event and sampling	No. of days between the last two events
Design of the system	Proximity of a system to vegetation
	Remaining volume in HRW system

3.3 EVALUATION OF SOLAR DISINFECTION OF *E. COLI* UNDER SUB-SAHARAN FIELD CONDITIONS USING A 25L BOROSILICATE GLASS BATCH REACTOR FITTED WITH A COMPOUND PARABOLIC COLLECTOR

In order to disinfect larger volumes of water than used with the 2L PET bottles, it was of interest to determine the effectiveness of a compound parabolic collector to disinfect water in Uganda. The experiment was carried out at the University of Makarere and the water tested was sourced from a well in local slum. Uganda typically has two rainy and two dry seasons per calendar year however the timing of these is no longer reliable due to the effects of climate change. For the period of this experiment April, May, August, September, October, November and December were rainy (wet) months (rainy season) while January, February, March, June and July were dry months (dry season). However, in between the rainy or dry seasons some days could be sunny or cloudy rainy. Data was recorded on 13 occasions over a 17 month period from May 2011 to September 2012. Data was not collected for the months of June 2011, August 2011, October 2011 and October 2012.

3.3.1 *Characteristics of untreated natural water*

The characteristics of the untreated water used in all the experiments are described in Table 3.12. The temperature and pH of the source water did not vary significantly ($p>0.05$) for the duration of the investigation. The temperature ranged from 22°C – 27°C and the pH from 6.0 – 7.7. The level of total dissolved solids (TDS) varied significantly ($p = 0.001$) with the season ranging from 26 – 63 mg l^{-1}in the rainy season and from 8 – 25 mg l^{-1}in the dry season. The levels of *E. coli* in the untreated water also varied from month to month. Higher numbers of *E. coli* were detected during the rainy season and corresponded with higher levels of dissolved solids.

Table 3.12: Physico-chemical and microbial quality of raw natural water collected from Kikonyi protected well

Exposure Date (MM/YY)	*E. coli* cfu/100ml	Temp. (°C)	pH	Total Dissolved Solids (mg l^{-1})	Season
05/11	136 ± 11	23.0	7.6	32	Rainy
07/11	117 ± 5	23.5	6.3	19	Dry
09/11	174 ± 30	25.0	6.8	40	Rainy
11/11	11 ± 2	23.0	6.8	47	Rainy
12/11	>300	23.8	6.0	55	Rainy
01/12	136 ± 14	27.0	6.4	12	Dry
02/12	190 ± 23	23.0	7.3	10	Dry
03/12	56 ± 15	22.1	5.8	21	Dry
04/12	230 ± 23	25.0	6.0	37	Rainy
06/12	91 ± 13	22.0	7.6	25	Dry
07/12	126 ± 6	22.0	6.0	8	Dry
08/12	>300	23.0	6.9	63	Rainy
09/12	105 ± 5	23.0	7.7	26	Rainy

3.3.2 *Effect of UVA+B on inactivation of E. coli*

Representative data for Sunny (a), Intermittently Sunny/Cloudy (b) and completely Overcast/Cloudy (c and d) months during the study period are presented in Figure 3.32.

Generally, a lag reduction during the first hours followed by a linear reduction and finally a tail was noted in most of the experiments. Despite the fact that all the experiments shown in Figure 3.32 were carried out during the rainy season, those that happened to be done on a sunny day achieved full treatment in one day while those on intermittent cloudy conditions took more than one day (10 hours) of exposure to achieve the full treatment of *E. coli*. The experiment that was carried out under cloudy conditions/ over cast days (April 2012) did not acquire full disinfection of *E. coli* even after the two full days of exposure. The noted differences under different conditions are likely to be due to differences in UVA+B levels. Generally, the experiments began in the morning with low levels of UVA+B which increased reaching a peak between t4 and t6 (1:00pm and 3pm) and then declined.

Almost half of the exposure time on cloudy days received UVA+B of below 30mW/m2 unlike on sunny days. For example on the first day of July 2012 (cloudy day), there were high levels of UVA+B of 46W/m2 for a few minutes at the begining of the experiment. The levels then dropped to below 30W/m2 for almost the next 5 hours (only two hours had UVA+B of above 30W/m^2 (Figure 3.32). However , on sunny days for example Sept.2012 (Figure 3.32 below) UVA+B of above 30W/m^2 for five hours was received and for such a day there was full treatment of bacteria in only 7 hours of exposure.

It is worth noting that the UVA+B levels for some of the experiments were not taken. Therefore the effect of UVA+B levels on to inactivation of *E. coli* in the current study is not compared

It is apparent that sunny (a) and intermittently sunny/cloudy (b) conditions are usually sufficient for complete inactivation of the bacteria to be achieved within the BGTR-CPC reactor within 7 hours of exposure. LRVs of 7-log units are observed within 6 and 7 hours for the Sept 2012 (sunny) and Aug 2012 (intermittently sunny/cloudy) conditions, respectively.

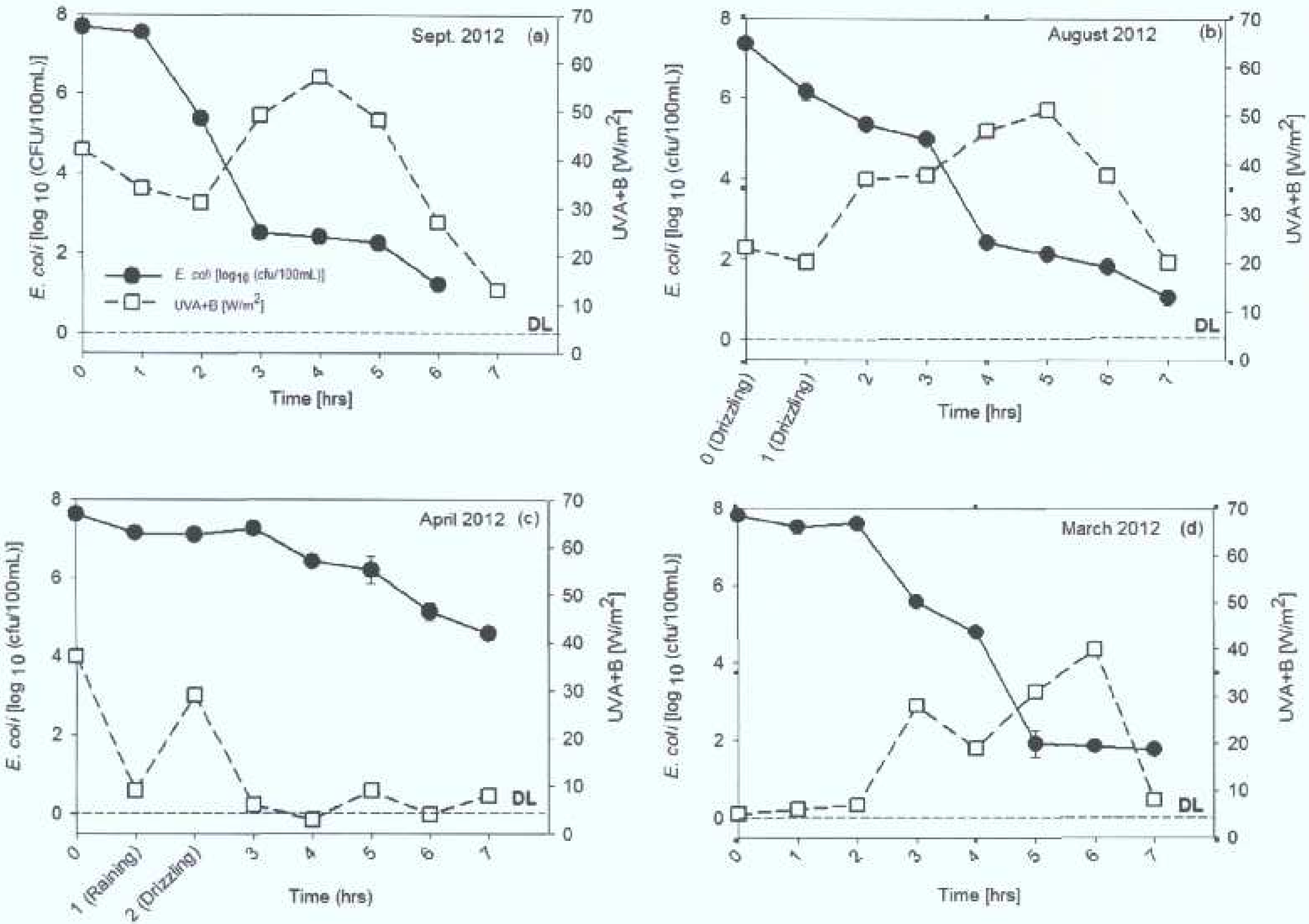


Figure 3.32: A comparison of bacterial inactivation (-) and incident UVA+B (-) for a representative sample of Sunny (a), Intermittently Sunny/Cloudy (b) and completely Overcast/Cloudy (c and d) months during the study period.

3.3.3 *Log $_{10}$ bacterial inactivation*

The April 2012 exposure was conducted under such rainy/overcast conditions that we suspected complete inactivation would not be achieved during the 7 hour duration of the experiment. Consequently the experiment was extended to the following day and the results of this two-day exposure are provided in Figure 3.33.

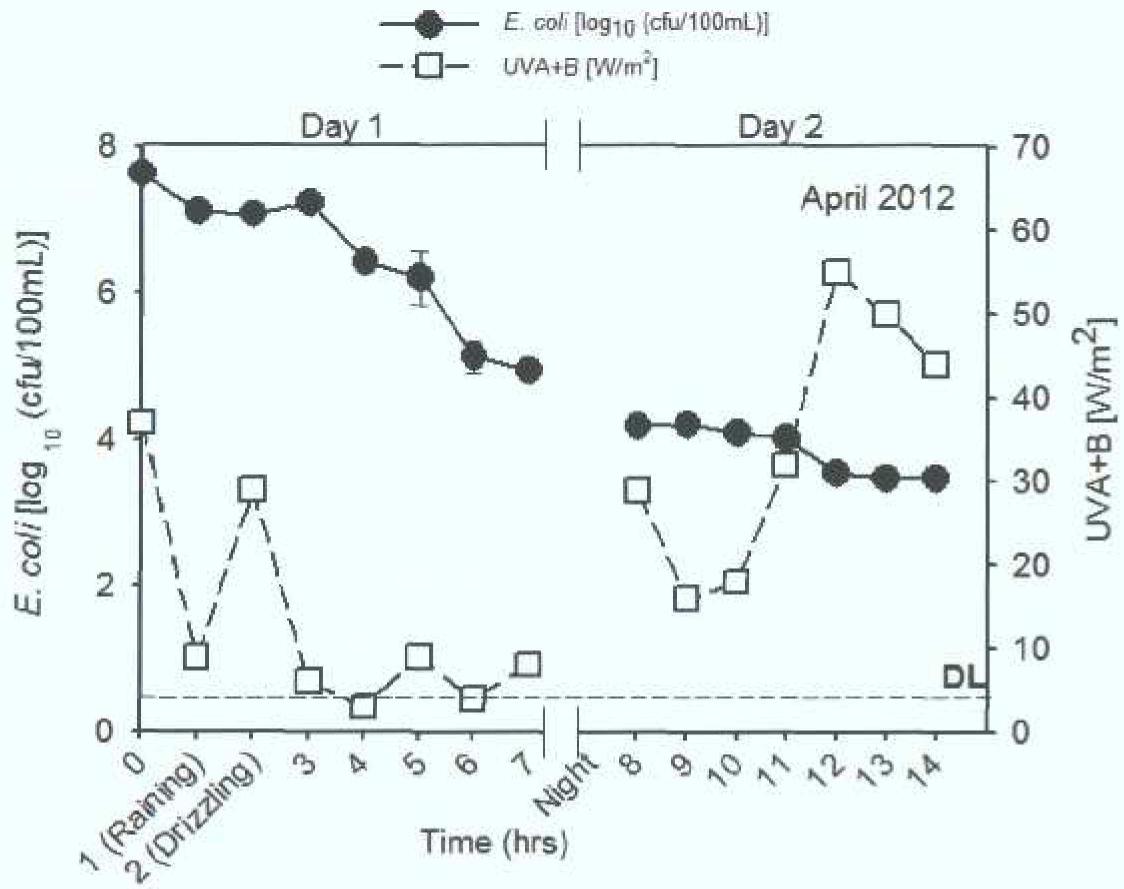


Figure 3.33: Bacterial inactivation (-●-●-●) and incident UVA+B (-◇-◇) over two consecutive days within a completely cloudy/overcast period in April 2012.

Despite improved cloud and sunshine conditions on Day 2 full inactivation was not achieved with final concentration remaining at 10^4 cfuCFU/100ml.

3.3.4 *Response of E. coli to solar disinfection using the CPC*

The response of *E. coli* to solar disinfection using the CPC was monitored over a 17 month period from May 2011 to September 2012. The results obtained on 13 occasions during this period are described in Figure 3.34 below.

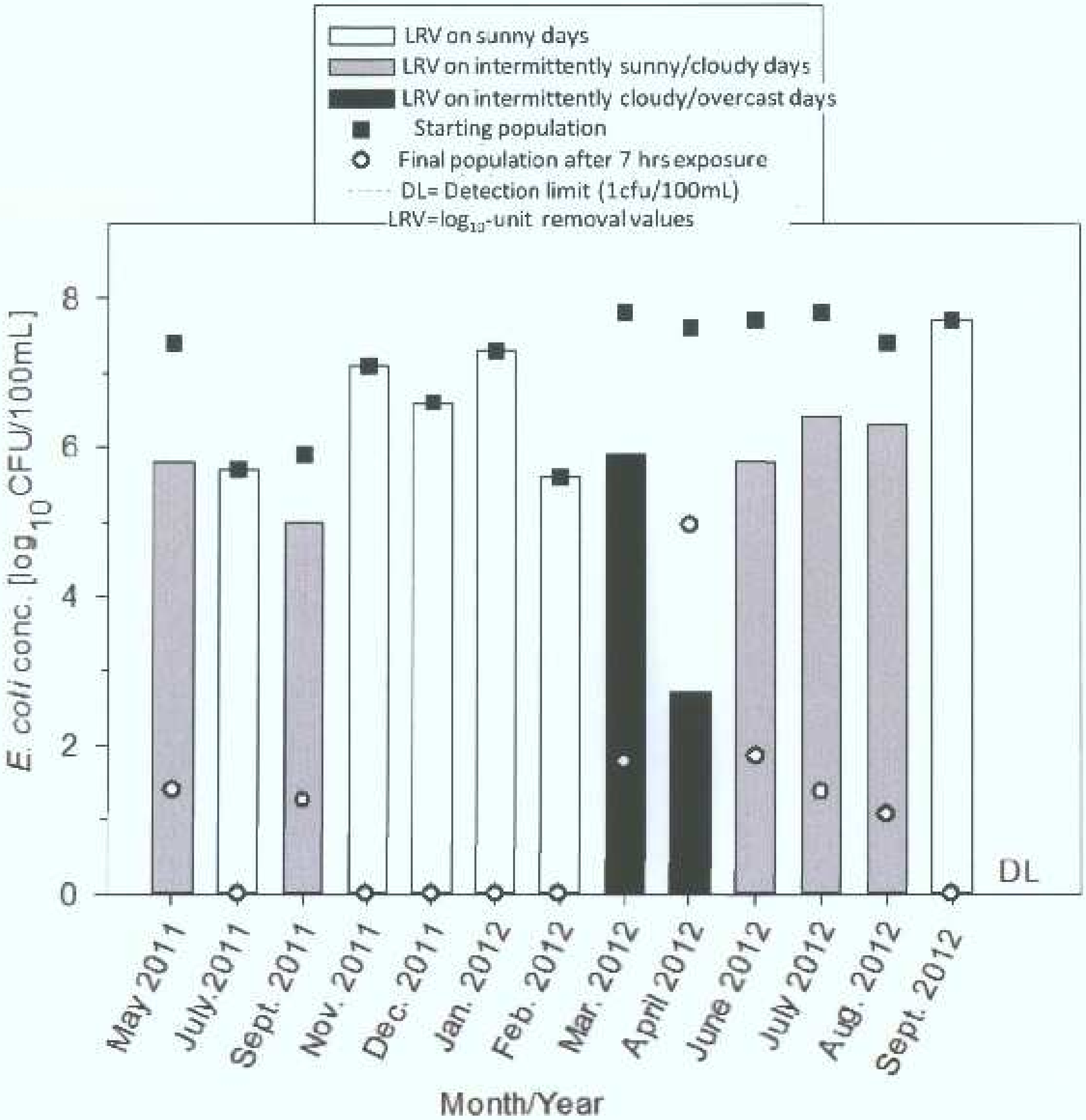


Figure 3.34: Summary of the bacterial inactivation efficacy of the BGTR-CPC over the 14 month study period. The length of bars represents the log10-unit removal values (LRV) for each day of exposure.

The initial inoculum size ranged from 10^5-10^7cfu/100ml. Figure 3.34 shows the starting population, final population after 7 hours solar exposure and the log_{10}-unit removal values (LRV) for all the experiments. Complete inactivation to below the detection limit (< 1 CFU/100ml) was achieved for all 6 exposures conducted under strong sunlight conditions. If we define satisfactory disinfection as one which produces either a LRV ≥ 6.0, as recommended by the US EPA (1987), or inactivation to below the Ugandan National Bureau of Standards guidelines (UNBS, 2009) for safe drinking water (< 1 cfu/100ml), then successful disinfection of the 25 liter batch volume was achieved in 11 of the 13 experimental investigations. Only experiments conducted in Sept 2011 (LRV = 4.5) and April 2012 (LRV = 3.0) failed to produce satisfactory disinfection levels. While the former was conducted under intermittently sunny/cloudy conditions and the latter under cloudy overcast skies, both exposures experienced periods of rain or drizzle. Dark controls showed no significant change ($p>0.05$) in bacterial numbers. Samples taken at the end of experiments and stored for 24 h before analysis also showed no significant change ($p>0.05$) in bacterial numbers indicating that there was no re-growth of *E. coli* after treatment with in the 24h. 24h were considered to be long enough based on literature. SODIS treated water is recommended to be consumed within 24h after treatment (McGuigan *et al.*, 2012). Several studies have also reported the use of 24h as sufficient time for examining regrowth in SODIS treated water (Meera and Ahammed, 2008; Navntoft *et al.*, 2008; Ubomba-Jaswa *et al.*, 2010).

3.3.5 *The effect of water temperature*

In all experiments temperature (°C) in the CPC was measured at intervals of one hour. Figure 3.35 below shows the maximum temperature attained during the CPC solar exposure. The starting temperature ranged from 21.9°C to 27.5°C with March 2012 and April 2012 recording the lowest temperatures of 21.9°C and 22°C respectively.
The highest temperature attained in the CPC experiments was in December, January 2012 and April 2012 of 37°C, 35.9°C and 36.1°C respectively.

In none of the experiments temperature reached 45°C which is required for synergy inactivation effect of temperature and solar irradiation for bacteria. In these experiments, months that showed the highest temperatures are not necessarily the same months that recorded complete inactivation of bacteria in the shortest time of exposure. This was observed with June 2012 experiments which is one of the months that recorded the highest temperature. Yet those experiments that recorded their highest temperatures being below 35^{0}C recorded complete inactivation in fewer hours than those experiments that recorded their highest temperature being above 35^{o}C except for April 2012 as described in Figure 3.35 below.

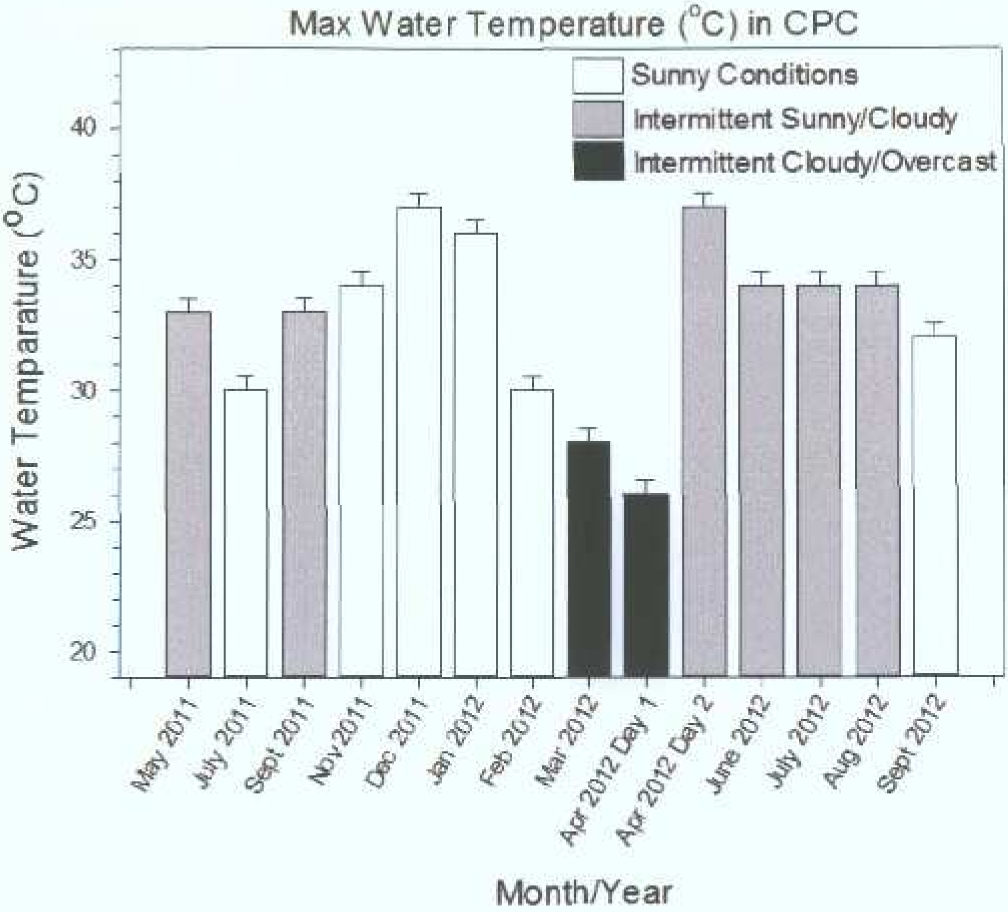


Figure 3.35: The maximum water temperatures achieved in the CPC for each experiment

4 DISCUSSION

Despite the several studies on both physiochemical and microbial quality of harvested rainwater (HRW) in other parts of the world, the harvested rainwater (HRW) in Makondo parish, Masaka Uganda had never before been studied. Hollander *et al.* (1996) reported that HRW was contaminated with *Pseudomonas* spp during the study on 102 German rainwater storage tanks that were being used for toilet flushing, garden irrigation and clothes washing. Out of 102 rainwater storage tanks, 12% were contaminated. Albrechtsen (2002) reported that the Danish rain water systems introduced microorganisms into households that were different from those organisms typically associated with water from community water systems. The study suggested that microbial populations were also influenced by different collection surfaces. Furthermore, the study suggested that improperly designed rainwater systems could increase the risks of infection to household water supplies, especially if cross contamination were to occur between Danish drinking water networks, and rainwater systems.

Levesqque *et al.*, (2008) reported a high frequency of faecal contamination in household HRW tanks in Bermuda which was attributed to ineffective preventive measures for water contamination by household. Martin *et al.* (2010) reported high microbial loads in rainwater storage systems which increased with a rainfall event, however, these were not sustainable as they gradually fell to baseline levels within the following 7 days. The authors also reported colonies with different morphologies on incubated membranes at 25°C but not at 37°C, however, these were thought to be of environmental origin since they were more adapted to lower temperatures. In the view of the above, a preliminary study was carried out to assess the microbial quality of HRW in Makondo sub-parish.

4.1.HOUSEHOLD SURVEY

Family size and socio economic status

Families in Makondo were found to have varying sizes of family characterised by varying levels of income. Households had between 5-12 people in a household. The majority (73%) of the households were extended families with more than 5 people. In agreement with the current survey, a study by Baguma *et al.* (2010b) in Luwero and Wakiso districts of Uganda also revealed that the majority (53%) of the households had more than 5people. This can be explained by the same culture in the two study areas. The two areas, Luwero and Wakiso districts are located in the central region of Uganda (Buganda) similar to the Lwengo-Masaka district where the current study was carried out. All these districts share the same cultural beliefs.

Makondo registered a higher household size of 6.5±3.2 when compared to the average national household size in rural areas of 5.3 (UBOS, 2010). The national average household size is reported to have reduced in rural areas by 0.1 from 5.3 in the year 2005/2006 to 5.2 in the year 2009/2010 (UBOS, 2010). Despite the fact that the average household size in rural areas is reported to have reduced, it is still higher than in urban areas of Uganda where it was reported to be 3.9 in the year 2009/2010 (UBOS, 2010).

The majority of the households studied were peasant farmers, their monthly income was far below 200,000 UgShs (80 US $). Only a few households had an income above 200,000 UgShs. These were mainly people who finished at least O level and they had some formal employment such as nursing, teaching and local council membership. In disagreement with UBOS (2010), the average monthly income of households in Makondo (120,000±32,000UgShs) was much less than the average monthly income reported by UBOS for the central region (Buganda) rural households for the year 2009/2010 (336,800UgShs). The Makondo monthly income, while similar to those in rural areas of Eastern and Northern Uganda at 151,400 UgShs and 117,200 UgShs respectively, was much lower than the average urban monthly household income of 959,400 UgShs. However, this is not surprising according to the findings of Ssewanyana (2009) who reported increasing chronic poverty with increasing household size in rural areas of Uganda.

Health status of members of the households

Although one would expect a significant level of water borne illness to be associated with the consumption of contaminated water, this was not the case. None of the respondents reported cases of cholera, dysentery or diarrhoea. The cholera findings agreed with Baguma *et al.* (2010a) which also reported zero cholera incidences in the Luwero district. However, contrary to the current study, cases of dysentery and diarrhoea in 6% and 81% respectively were reported in this district. The difference in the findings could have been due to different methods used in data collection. Baguma *et al*. (2010a) used the ministry of health district records while the current study interviewed the local households. In the current study people responded according to what they were told in clinics or what they felt they had in the case of those who used traditional medicines. The other possible cause of the different results could be the nature and sample size. The current study interviewed only 30 households who were engaged in HRW use while Baguma *et al*. (2010a) considered health records for about 11600 outpatients which were using all sorts of water sources. In the two studies, incidences of typhoid were reported.

Water Usage and Use of HRW water

In Makondo, the average amount of water used per person per day was 12±3.5L. This was slightly higher when compared to other rural parts of Uganda,. In a study carried out by Sugita (2006) in Bugobero (another rural area in Mbare district- Uganda), the average amount of water per person per day was only 7.87± 2.03L. The reason for the high per capita water usage in Makondo compared to Bugobero could be due to the fact that all the households surveyed in the current study had HRW tanks unlike in the Bugobero study. Sugita, (2006) pointed out that the availability of HRW tanks at households increased the per capita water usage by 2.08 L (26%).

A higher per-capita water usage per person (15.42±0.50 L) than that obtained in the current study or the study by Sugita (2006) was reported by Mellor (2009) for three rural based districts of Uganda. However, the higher per-capita water usage in the three districts could be attributed to the larger sample size of 1,563 respondents in the Mellor (2009) study compared to 30 and 50 respondents in the current study and the Sugita (2006) respectively. Furthermore, some parts of the districts surveyed by Mellor (2009) are peri-urban with centralized water supply. In Kampala the capital city of Uganda, on average a person uses about 20 L of water per day (UBOS, 2012).

At least 50 L of water per person per day are recommended (Gleick, 1998; WHO, 2014) for adequate sanitation and hygiene. Gleick (1998) recommends a minimum water requirement of 5 L for drinking, 20 L for sanitation, 15 L for bathing and 10 L for food preparation to sustain life. However, in both the studies in Uganda, the per capita water usage per person is far below the amount recommended. In developed countries like the USA, a person uses about 303-379 L per day (US EPA, 2010a) about 10 times that used by a person in Makondo.

The average levels of water consumption in rural areas of China is reported to range from 47-71 L depending on the availability of piped water (Fan *et al.*, 2013). The majority of the villages in Uganda, however, have no access to piped or tapped water.

Use of HRW water

In Makodo-Lwengo-Masaka, the main objective in harvesting rooftop rainfall is to collect drinking water which is perceived to be of better quality for drinking than water from other sources. Other uses of HRW, including watering animals and washing clothes, are only used when HRW is in excess especially in the middle of the rainy season. Harvested rainwater is considered precious for drinking purposes. During the dry season, HRW is used only for drinking purposes and water from other sources like boreholes and wells is sourced for other activities like washing dishes, bathing, laundry and watering animals.

Although almost all people in Makondo practice some form of harvesting rainwater on varying scales for drinking, they also rely on other sources of water like boreholes, protected wells and open dug wells whenever HRW is not sufficient. In fact, some households were found using more than two water types especially in a dry season. A single household would be using HRW for drinking, borehole water for laundry and cleaning dishes and also open dug well water for water animals. However, it should also noted that during very long drought spells HRW, borehole and protected well water becomes very scarce which lead people to resort to open dug wells for drinking water.

The household's choice of water source depended mainly on quality perceptions, the distance of the source from a home stead and waiting time (queue) at the water source. Households were found using water from different sources for different household activities due to perceived water quality (water safety) and distance from the water source. For example, during scarcity of HRW in the dry season, a household would source drinking water from a borehole or a protected well while from an open dug well for other household activities. Participants in the current study used water taste, odour, and clarity to perceive water quality. Respondents defined safe drinking water as that which is clear (transparent) with no odours and taste. Therefore, a water source would be defined safe or of better quality to be used for drinking depending on these three factors. These findings are in agreement with Banda *et al.* (2007) and Wright *et al.*, (2012). In rural areas of India, clarity, lack of odours, and an un salty taste were given as the characteristics of safe water. Likewise in rural areas of South-Africa, respondents perceived drinking water safety as primarily the lack of water taste, odour, and also water being clear rather than socio-economic or demographic characteristics (Wright *et al.*, 2012).

In the current study women reported to prefer sources near to their households. One of the reasons given was that lifting jericans of water for longer distances make their bodies pain. The current findings are in line with Sandiford *et al* (1990) who reported increased per capita water use per person per day as a result of reduced distance from the water source. The current findings are also in agreement with Gazzinelli *et al.* (1998) and Stefanie *et al.* (2005) who pointed out that the further the distance from the water source the less people use the source. The current findings also align with Arouna and Dabbert (2010) whose findings revealed that the quantity of purchased water used by a household increased with time required for fetching water from a free source.

Contrary to the current findings, Whittington *et al.* (1990) reported that women prefer sources that require longer walking distances with longer queues. This could be because in the past the main role of women was household based work without engagement in any income generating activity. However, due to the increasing cost of living, women both in rural and urban areas are becoming involved in income generating activities for example poultry, piggery, art and craft, selling little kiosks etc. Therefore, saving time by fetching water from nearby sources is economically of great benefit to these women.

The cost HRW systems/tanks in Makondo

The reported cost of HRW tanks varied widely in Makondo. Some tanks were donated to vulnerable households by an NGO at no cost. However when bought by the household, the cost of the tanks was reported to range from 300,000UgShs (115US$) to more than 700,000UgShs (270US$). The cost varied depending on the size of the tank and the material used. Constructed tanks were found to be cheaper than pre-fabricated ones. For both types of tank smaller tanks (low volume) were found to be cheaper than bigger volume tanks. However, when cost per litre of water stored was computed, it reduced with tank size. The current results are in agreement with the findings of Parker *et al.* (2013) in which constructed tanks were also found cheaper than prefabricated ones in East Africa. The authors also reported that tank size was also important in determining the cost of the tank and it increased with the tank size. Parker *et al.*

(2013) in addition reported that the tank cost per litre stored decreased as size of the tank also increased. However, Parker *et al.* (2013) reported lower costs for both prefabricated and constructed tanks than in the current study where the costs were almost double the costs reported by Parker *et al.* (2013) for constructed concrete tanks of similar volume. In the study by Parker *et al.* (2013), a concrete 1500L tank was found to cost US$76 (200,000 UgShs) while in the current study, the same tank was found to cost US$153 (410,000 UgShs). Also a 25,000L concrete tank of the same material was found to cost US$361 (950,000 UgShs) by Parker *et al.* (2013) yet in the current study, this was reported to cost about US$730 (1,900,000 UgShs). The differences in the findings can be explained by two factors. Firstly the inflation rates in recent years. Parker et al. (2013) carried out the survey in 2007 when a dollar was equivalent to about 1750UgShs while the current study survey was done in 2011 when a dollar was equivalent to 2500UgShs. The second reason could be the differences in methodology. Parker *et al.* (2013) got the prices by purchasing the prefabricated tanks from local factories and also constructed the tanks themselves while in this study, costs were determined by asking the households directly. Although Uganda is reported to have gained a high gross domestic product per capita of US$623 (IMF, 2014), it is much lower in rural areas. Hence buying HRW systems remain expensive and not affordable to many rural households. This further highlights the need for Government and NGO support to help rural communities in Uganda access HRW facilities.

Time saved when using HRW and activities done

Households in the area studied reported saving time when using HRW instead of fetching water from other sources. This time was considered to be very valuable and was used productively for many activities for example farming, art and craft some of which are income generating. These results are agreement with those of a number of other studies (Whittington *et al.*, 1990; Ilahi, 2000; Gupta, 2009; Arku, 2010).

Whittington *et al.* (1990) indicated that households in Ukunda village- Kenya placed a surprisingly high value on the time they spend collecting water. The study of Ilahi (2000) reported that the increased time spent in accessing water significantly alters women's work patterns and adversely impacts on income-generating activities of their households. Gupta (2009) showed that the existence of a source of drinking water in rural areas is one of the most important indicators of development that reflects the economic prosperity of a village. The study in addition showed that villages with a piped water supply have higher levels of household and per capita income in India. Water supply was also linked to social improvements including high immunization rates, literacy, and contraceptive prevalence rates. Arku (2010) who focused on noting the positive effects on women when time is not spent collecting water also reported improved women's well being. This was also reflected in this study which showed the involvement of women in productive activities during the time saved when using HRW which in turn added to the wellbeing of their family.

Water safety

Nine (56%) households out of 16 who reported to be using water that they felt was not safe for drinking mentioned that this is because they take it without any treatment like boiling. The rest of the respondents (44%) felt that it was not safe because of a bad taste. Although a lot of efforts have been put into promoting HRW in rural households, knowledge about the safety of HRW and how it can be ensured is as yet not adequate. The majority of respondents in the current study reported to have been consulted about safe drinking water by NGOs and volunteers like students. However, a big number reported to have been ignorant about the safety of the HRW they were using. About 30% of the respondents didn't have any idea about the safety of HRW they were using. In agreement with Baguma *et al*. (2010a) the majority of the respondents (95%) were not taking care of the safety of HRW as they were not cleaning gutters or tanks.

Studies have linked drinking contaminated and educational level and gender (Pradhan, 2004). Educated families were found to be more informed about safety of water than uneducated families which he associated with knowledge attained from schools about water, sanitation and hygiene (WASH). This explains the high percentage (30%) of Makondo households who did not have any idea about the safety of the water they were using since Makondo is a village dominated by peasant farmers with little education.

Water treatment

Intentions to treat drinking water in households have been shown to be influenced by perceived vulnerability (susceptibility) of water users to consequences of consuming contaminated water by Heri and Mosler, (2008) and Mosler and Kraemer, (2011). These two studies suggested that the more one feels vulnerable, the more likely one will treat drinking water. The majority of the households (80%) in this study reported consuming water without any treatment or purification. When asked why they do not treat water, participants reported economic concerns where fuel to heat water is scarce and also the unacceptable smell of chemically treated water. However, the few who claimed to be applying some treatment reported to be mainly using boiling. The current findings are in agreement with the findings of Baguma *et al*. (2010a) who reported that although 70% of the respondents reported to know about the chemicals used to treat HRW for drinking purposes, 80% reported to have never used any. The reported high vulnerability (susceptibility), lack of resources for boiling (the most traditional household water treatment method) and the unpleasant smell of chemically treated water indicated the need for a more sustainable method such as SODIS for treating HRW in Makondo.

It was difficult to cost the treatment of water. Those using boiling had no idea of how much it was costing them since they felt that they were getting firewood at no cost. The water guard users also reported to be getting the tablets at no cost from NGO programs that are supporting HIV victims in the area. However, when firewood users were asked on how much they would get for selling the firewood they estimated between 800-2,000UgShs (about 0.87 US$) per month and 2,000 to 4,000UgShs (about 1.8 US$) per month. Although Chlorine tablets/ water guard users reportd to be getting them for free, it currently costs $0.038 (100 UgShs) to treat 20L of water if purchased from local drug shops (personal communication). This is more expensive compared to the past years. Chlorine tablets/ water guard (sodium hypochlorite) used to cost about $0.27 (702UgShs) per person per year to treat 1000L of water in Uganda (Shrestha *et al*., 2006). However, it is currently seven times more expensive costing $1.92 (5000UgShs) to treat the same amount of water. This is also relatively more expensive compared to neighbouring countries like Tanzania where it costs about $0.19 (500UgShs) per person per year to treat 1000L of water (Clasen and Edmondson, 2006).

Knowledge of SODIS

Although one of the respondents reported to have heard about SODIS through a friend, the respondent had not ever practiced it in her life. The respondent attributed this to lack of convincing information on how SODIS disinfects water. The respondent explained that she used to doubt the technology because she was told there is no chemical added to water when doing SODIS. In addition she was told that the water does not boil like in the traditional way. Therefore she was uncertain about what kills germs. This is consistent with the findings of EAWAG/SANDEC (2002) where one of the barriers for adopting SODIS is reported to be uncertainty about the effectiveness of the technology among the users ('don't trust the method). In the current study, the majority (97%) of the respondents had no idea about SODIS irrespective of education level because it had never been introduced in this area. Also in schools, children are taught about drinking water treatment methods however, SODIS is not yet included in any of school's curricula. With this background, the introduction of SODIS was thought to be a good technology for drinking water treatment in the Makondo area.

4.2.PRELIMINARY STUDY

The preliminary study was conducted for four months which included two dry and two wet months. The physiochemical parameters of RHW tested were dissolved oxygen, temperature, pH and TDS.In addition to HRW, other sources of water which were being used by households in the absence of HRW especially in the dry season were examined, for example boreholes and wells. During the first two months (April and May), all samples were HRW since they were rainy months. However, in June and July some samples of boreholes and wells were analyzed. The temperature of HRW ranged from 19.5to 29.0°C during the four months of the preliminary study. However, during the yearlong study in some months like March 2012, it increased upto 33.6°C. This is explained by two factors, the time of sampling in the day and the months of the year, which were not covered during the preliminary study. During the preliminary study the samples were fewer and all sampling was done during morning hours before the hottest hours of the day unlike during the yearlong study when samples were taken until in afternoon when temperatures would be at their peak. The other factor which might have contributed to relatively high observed temperature was the period of the year, for example January to March, which are the hottest months of the year in Makondo-Lwengo-Masaka and none of these months was included in preliminary study. Like temperatures, there were some small differences in other physiochemical parameters (pH and TDS) and these are all explained by the above possible factors. During the first two months in which dissolved oxygen of HRW was measured, it ranged from 2.4 to 7.6mg/l.

The temperature of other sources of water (bore holes and wells) ranged from 27.8 to 29.3°C which did not significantly differ (p=0.08) from that of HRW. This is explained by the fact that the samples of water from borehole and wells were from the containers of the respective households and not taken from the actual sources. Most of these containers were 20L jerrycans (plastic containers) and were exposed to sunshine after collection. The pH of the majority of other sources of water was also generally neutral like that of HRW with an average value of 5.9±1.3. Total dissolved solids values of other sources of water and HRW were also generally in the same ranges although the minimum TDS (48mg/l) in other sources of water was generally higher than that of HRW (8mg/l). It's worth noting that the results of HRW and those of boreholes and wells cannot be compared since the sample size (n=9) was generally too small compared to 47 samples of HRW.

During the preliminary study, the microbial quality of HRW was also examined using HPC, TTC, *E. coli* and faecal enterococci during the first two months of the study. Based on all these parameters, the majority of HRW samples were not safe for drinking and required treatment. Although HPC, TTC and TC were also used in the first two months and they all showed comparable results to *E. coli* and faecal enterococci, they were not used in the following months. Using more than two traditional indicators would be very expensive. *E. coli* has been documented to make over 70-80% of all TTC (Rasmussen and Ziegler, 2003; Garcia Armisen *et al*., 2007; Hachich *et al*., 2012) and therefore measuring both TTC and *E. coli* would be a waste of resources. Also many studies have recommended *E. coli* as a better indicator organism for faecal contamination in fresh waters than TTC (US EPA, 2004; APHA, 2005; WHO, 2008).

In addition, organisms like HPC are mainly environmental (WHO, 2008) and less sensitive in detecting faecal contamination, compared to *E. coli* and faecal enterococci. Therefore the presence of HPC would have fewer implication about the microbial safety of HRW. Since the majority of the HRW samples in these first two months of the preliminary study were unsafe for drinking hence requiring treatment, SODIS was then introduced as a treatment for harvested rainwater. Faecal enterococci survive longer in the environment (WHO, 2008, 2011; Ahmed *et al*., 2013) than *E. coli*. Therefore they were suitable for detecting longstanding contamination which would not be the case for *E. coli*. However, *E. coli* is more resistant to solar radiation (Wegelin *et al*., 1994; Ahmed *et al*., 2013) therefore, it was suitable for testing the safety of HRW for drinking after SODIS treatment. For this reason, the raw and SODIS treated water samples were tested for both *E. coli* and faecal enterococci.

As in the first two (wet) months of sampling, the majority of the samples in the following two (dry) months were contaminated with levels of microbial indicators above those recommended by WHO (2011) and UNBS (2009). However, the levels of indicator organisms were slightly lower than in the first two (rainy) months. This indicatespossible variations in the microbial quality of harvested rainwater in the different seasons which forced me to do a yearlong study to investigate on the possible seasonal variations in the microbial quality, whose findings are discussed in the section of yearlong study below. During the first month of the SODIS trial in the preliminary study, samples of HRW from Makondo were also treated from the university roof by myself to be compared with those that were treated by the local households in the field. Samples of HRW that were treated from the University roof by myself were less contaminated than those that were treated by the households in the field. The findings show that if SODIS is done efficiently following the right procedures, treatment efficiencies of up to 100% can be achieved. The other sources of water which were also sampled showed generally high treatment efficiencies for both those samples treated from the field and university roof which were comparable to those of HRW in the two places. However, as noted for physiochemical parameters, the sample size of other sources of water was considerably low compared to that of HRW for comparison.

4.3.PARTICIPATION

After introducing this study to the Makondo community, many people showed a lot of interest and were very eager to be part of the project. In training meetings, the high number of participants was far beyond the expected number. Before the project, a lower rate of participation was expected since participarts are used to be facilited in most of the Governmnt trainings unlike in the current study. Because of the high unexpected participation, the recruitment procedure was further tightened with easy accessibility to their respective HRW systems. The overall participation was generally good, however, this was motivated by giving households four (4) SODIS bottles twice a year. By the end of study three participants had dropped out due to illness or death. In disseminating SODIS, it's of great importance to help people recognize the great need of treating their water (Kraemer and Mosler, 2010). Therefore, before training on how to carry out SODIS treatment in the current study, a preliminary study was conducted to establish the microbial quality of HRW. The results were used to show/demonstrate to people the need to treat their water before drinking. Opinion leaders play a key role in promoting SODIS with relatively cheaper resources (Tamas *et al.*, 2009).

Therefore, the current study started by visiting local leaders (Local councils level 1 chair persons) in the area hence creating ownership of the project/ study. A local facilitator who is a born in one of the villages in the study was used as a SODIS promoter during the first months of the study. The SODIS trainings always started by educating people about Water, Sanitation and Hygiene (WASH) as recommended by several authors (EAWAG/SANDEC, 2006; Rainey and Harding, 2005).

4.4.IMPACT OF CLIMATE CHANGE ON RAINFALL AND SEASONS

There was a significant variation of rainfall between months ($p < 0.05$) and this is explained by the two rainy seasons experienced between March–May (MAM rainfall) and September – November (SON rainfall). In the current study, rainfall data was collected and the two seasons were studied, however, these were different from the usual timing due to effects of climatic change. Uganda is known for a bimodal pattern of rainfall that consists of two wet and dry seasons in a year. The two wet seasons have been traditionally been March-May (MAM rainfall) and September to November (SON rainfall) (MWE- DWRM and meteorology, 2002). However, with the effects of the climate change the total monthly rainfall for the study area have fallen during the last 20 years in addition to the timing of these seasons. March has been traditionally known as a wet month receiving a total monthly rainfall of about 140.4mm (climatological base period of 1961 – 1990), however, in the current study it was about 44.2mm which makes it almost a dry month. August was another month which recorded greatly reduced total monthly rainfall. August 2011 and August 2012 recorded 43.3mm and 24.2mm, respectively, compared to the average long term monthly level of (August) 53mm (climatological base period of 1961 – 1990). According to average long term rainfall (climatological base period of 1961 – 1990), December used to be a relatively wet month receiving about 82mm of rainfall, however, in the current study the month recorded only 32.1mm. The current findings are in agreement with a number of reports which have also documented the general reduction in the rainfall received in Uganda. Basalirwa (1995) predicted more drying conditions for low lying areas like Lwengo District, which is confirmed by the current findings, which showed reduced rainfall for all the months studied apart from October 2011. The current findings are also in agreement with McSweeney *et al.* (2008) who predicted falling rainfall in MAM rainfall. Osbahr *et al.* (2011) also predicted overall reducing rainfall amounts in the country which is in agreement with the current findings. Although the current findings agree with Kansiime *et al.* (2013) which predicted falling amounts of MAM rainfall, it contradicts with the current findings on SON rainfall findings. Kansiime *et al*. (2013) predicted increasing SON rainfalls in the eastern parts of the country, however, the current findings show a falling trend in the central region of Uganda.

4.5.PHYSIOCHEMICAL PARAMETERS

Based on physic-chemical parameters (pH and TDS), the majority of the systems contained safe drinking water as recommended by WHO (2011). These findings are in agreement with the findings of Uba and Aghogho (2000); Adeniyi and Olabanji (2005). The majority of HRW systems in southwest Nigeria meet the recommended standards of potable water according to WHO drinking water guidelines.

Although the pH of HRW systems ranged from 4.8 to 8.9, for the majority of the systems it was generally around neutral with an average of 6.9±0.7. The pH values were in agreement with Lee *et al.* (2012). The researcher investigated the quality of HRW collected from roofs of different roofing materials and all the systems studied had pH values which were neutral or near-neutral ranging from 6.0 to 7.9. Although, Lee *et al*. (2012) showed pH variations in HRW due to different roofing (collection catchment) types, in the current study, this effect was not assessed since all the 48 out of the 50 (92%) of the collecting roofs were galvanized iron sheets. In the current study, pH varied among HRW storage systems made of different materials with concrete tanks registering the highest pH values. However, these variations were not statistically significant ($p<0.05$). The highest pH in HRW systems were those collecting water from concrete tile roofs (Lee *et al*, 2012). The high pH was attributed to the reactions between direct rainfall and alkaline components of the concrete tile roof. This could also explain the slightly higher pH values in concrete tanks in the current study. In studies carried out in Nigeria on HRW, slightly increased pH values in tanks collecting water from concrete slate tiles were observed (Uba and Aghogho, 2000; Adeniyi and Olabanji, 2005). The current findings are in agreement with those of Sazakli *et al.* (2007) where the average pH value obtained was in range recommended by WHO (2011) for safe drinking water. The authors studied the quality of HRW in the northern area of Kefalonia Island in South West Greece and pH values ranging from 7.6 to 8.8 with a mean value of 8.4 were obtained.

Based on TDS, all samples had TDS levels that were safe for drinking water. The TDS levels were all below 600mg/L as recommended by WHO (2011) and UNBS (2009) for safe drinking water. These findings are in agreement with those of Lee *et al.* (2010) where the TDS values of HRW ranged from 40 to 230mg/l which was within the recommended WHO (2011) safe drinking water guidelines. However, Lee *et al.* (2010) reported that the rainwater (rain runoff) collected in reservoirs had 280 to 1200mg/lTDS which was far above the recommended WHO (2011) safe drinking water guidelines for TDSof ≤600mg/L. Zhu *et al.*, (2004) reported that the majority of HRW from sloped land and roads in different catchments in China were far above the recommended WHO (2011) guidelines. This shows that the collection method matters a lot when it comes to TDS levels for HRW.

4.6. MICROBIOLOGICAL QUALITY OF HRW

Harvested rainwater HRW is of great socio-economic importance in areas where water sources are scarce or polluted (Zhu *et al.*, 2004). One of the main advantages of rainwater harvesting is the provision of water at or near the point of consumption, reducing operation and maintenance problems and running costs. Moreover, the physical and chemical properties of rainwater are usually superior to sources of groundwater that may have been subjected to contamination (UNEP, 2002). In the present study, the examined HRW samples met the requirements for safe drinking water in terms of physical-chemical parameters tested that is pH and TDS.

Despite the acceptable physical-chemical quality of the harvested rainwater, the presence of microbial indicators makes it unsuitable for drinking without any treatment. Although some studies have reported HRW to be generally of good quality with the majority meeting the international safe drinking water standards (Handia *et al.*, 2003; Dillaha and Zolan, 1984). In the current study HRW was generally of poor drinking standards with the majority of the systems contaminated and containing water that was not safe for drinking without treatment. *E. coli* and faecal enterococci were detected in the majority of the samples taken in this study. In the 12 months of the main study, out of 462 samples of HRW taken, 66.5% were contaminated with *E. coli* and 77.5% were contaminated with faecal enterococci at levels above the recommended safe drinking water guidelines of zero cfu per 100ml. The findings of this study are in agreement with the results of a number of other authors who reported HRW being contaminated and unsafe for drinking prior to treatment. For example, 72% of HRW had levels of *E. coli* exceeding the guidelines (Lee *et al.*, 2010). The current findings are also in agreement with Simmons *et al.*, (2001). In Auckland, New Zealand, 70 out of 125 (56.0%) HRW systems (roof collected rainwater) were unsafe for drinking prior to treatment. Zhu *et al.*

(2004) used faecal coliform as the indicator to study the microbial quality of harvested rain water in the arid and semi-arid Loess Plateau of northern China and the systems studied were unsafe for drinking. Howard *et al.* (2006) also reported 60% of HRW systems in Bangladesh contaminated with TTC and thus unsafe for drinking. Sazakli*et al.* (2007) studied the microbial quality of HRW in Kefalonia Island, Greece and showed that 80%, 41% and 29% of the rainwater samples collected respectively had levels of total coliforms, *Escherichia coli* and enterococci above the recommended safe drinking water standards of WHO (2011).

Levesqque *et al.,* (2008), also reported a high frequency of faecal contamination in household tank rain water collected during a study of 102 households in Bermuda. Radaideh *et al.* (2009), reported 55%, 40% and 15% of samples contained detectable levels of total coliform, faecal coliform and *E. coli*, respectively. In Bangladesh, Karim (2010) reported Total coliforms in 33%, 18%, 33% and 40% water samples collected from plastic, brick, ferrocement and roller-compacted concrete *(RCC)* reservoirs, respectively. Thermotolerant coliforms and *E. coli* were also detected in 13% and 14% water samples, respectively exceeding both the Bangladesh Drinking Water Standard and WHO. Lee *et al.* (2010) also showed that 91.6% and 72% of the total samples of HRW in Gangneung city of Korea were contaminated with TC and *E. coli*, respectively, at levels exceeding the Korea National Guidelines for Drinking Water.

Jesmi *et al.* (2014) reported over 70% of the HRW samples from central Kerala, India were contaminated and not safe for drinking without treatment. Consistent with the current findings from which HRW water showed seasonal microbial variations, in Bangladesh HRW was also reported to show seasonal microbial water quality (Rahman *et al.*, 2014). However, contrary to the current findings, Rahman *et al.*, (2014) reported low numbers of total coliforms and faecal coliforms at first when rains had just been harvested but kept on increasing after the rains. The authors associated the increasing levels of microbes after collection to poor maintenance as a result of inadequate rainfall. Yet the levels of microbial indictors in the current study were highest at the onset of the rainfall season and gradually fell with the reducing rainfall with minimum numbers during the dry season and the peak occurring in the wet season. The differences in the finding of these two studies can be explained by two factors; differences in design and cleaning (maintenance practices). It could be that in the systems studied by Rahman *et al.* (2014), there were diverts connected to gutters which would flush away the first rains or the first rains were flushed away after collection, unlike in the systems considered in the current study, which did not have diverts or the flushing of the first rains.

4.6.1. SANITARY RISK SCORE OF HRW

Sanitary inspection and water quality testing were recommended as complementary activities and the findings of each assists in the interpretation of the other (WHO, 2011). Sanitary risk scores are useful indicators of microbial contamination (Lloyd and Bartram, 1991; Karim, 2010). Karim (2010) noted that the overall sanitary conditions of most of the HRW systems were assessed as good. However, the sanitary conditions of the majority of the systems investigated in the current study were poor. None of the systems Karim (2010) studied had a risk score of above 5 (no systems was at high or very high risk) unlike in the current study where 43% of the systems had a risk score of above 5 (41% at high and 2 % at very high risk). These differences could be attributed by differences in levels of income. The south west part of Bangladesh where Karim (2010) carried out the study may have a higher income and thus better maintenance and design of HRW systems than in the rural Makondo-Masaka area of Uganda. Baguma *et al.*, (2010) noted that the level of income in a household greatly influences the management of HRW.

Although in some studies a strong correlation has been reported between microbial indicators used and the sanitary risk score (Howard *et al.*, 2003; Haruna *et al.*, 2005), this is contrary to the current findings. In the current study, a very weak correlation was found between the median *E. coli* levels and the median sanitary scores. The same weak correlation was observed between the median faecal enterococci levels and the median sanitary scores.

4.6.2. FACTORS INFLUENCING MICROBIAL QUALITY

The most important causes and thus likely control measures for contamination can be identified by a combined analysis of sanitary inspection and water quality data. This is important to support effective and rational decision-making. For instance, it's important to know whether on-site or off-site sanitation could be associated with contamination of drinking-water, as the remedial actions required to address either source of contamination will be very different. This analysis may also identify other factors associated with contamination, such as heavy rainfall.

Although the amount of rainfall was suspected to be one of the main factors influencing the microbial quality of HRW, in the current study no significant ($p>0.05$) correlation between the median levels of microbial indicators (*E. coli* and faecal enterococci) and monthly total rainfall was observed. This indicted that the microbial quality of HRW was not solely influenced by rainfall amount but also by other factors. These findings are in agreement with those of Howard *et al.* (2003) who observed no significant correlation between the median levels of faecal streptococci and monthly total rainfall. Therefore, in this study tree models were developed which revealed that besides the amount of rainfall other factors like condition of drainage of water collection area; distance between HRW system and vegetation; volume of water remaining; number of days between last rainfall event and sampling ; design of the system; mode of water abstraction; season; the number of rainfall events in a month; amount of rainfall in a month; level of education; size of household; temperature; number of days between the last two events also influenced the microbial levels in HRW. This sugggests that direct sources of contamination played a greater role in contributing to contantamination of HRW than the pathways (inderect means). For example, some of the pathways which were suspected to be influencing the quality of HRW were proximity of pit latrines, however, this was found not significant ($p>0.05$).

For both *E. coli* and faecal enterococci, the condition of drainage of the water collection area was the most significant factor influencing their levels in HRW. Usually the drainage of the water collection area is concrete with a sloping floor to allow complete drainage. However, in many of the systems sampled in the current study, these areas were not concrete and therefore they could not be fully drained. The stagnant water in these areas was probably sources of contamination as a result of splashing water during water abstraction.

Results showed increased levels of *E. coli* immediately after a rainfall event which reduced with time. HRW systems that were sampled during rains or after only one day of rains had significantly ($p<0.05$) higher levels of *E. coli* than those that were sampled after more than a day of rains. The increased contamination levels imediately after a rainfall event supports the general theory of rapid recharge and deterioration in microbiological quality in response to rainfall. i.e, direct entery of microbes probably from the catchment roofs. When rainwater comes in contact with a catchment surface, it can wash bacteria, molds, algae, fecal matter, other organic matter, and/or dust into storage tanks (Thomas and Grenne, 1993; Vasudevan, 2002; Pitkänen *et al.*, 2008; Helmreich and Horn, 2009; Amin and Han, 2011).

Thomas and Grenne, 1993; Vasudevan, 2002 suggested that the longer the span of continuous number of dry days (days without rainfall), the more catchment debris is washed off the roof by a rainfall event and therefore the higher the microbial load. This is in disagreement with the current findings. In this current study using a tree model, the number of continuous dry days between the last two rainfall events didn't show a significant effect on *E. coli* levels in HRW but instead did affect faecal enterococci levels. The current findings suggested that if the continuous number of dry days (days without rainfall) are more than seven (a week), then the levels of faecal enterococci will instead fall. This can be attributed to the disinfection effects of sunlight and high temperatures. If the days are more than 7 (a week) without rainfall, it's more likely to be a dry season with very high levels of sun radiation and high temperatures. Since in the current study, most of the collection roofs were galvanized iron sheets which can be as hot as 80°C, this resulted in a disinfection effect. Lee *et al*. (2012) also showed significantly less contamination levels in HRW that was collected from galvanized iron sheets compared to other types of roofs. These authors greatly attributed this to high ultraviolet light and the high temperatures which could have acted as disinfection agents.

Despite the fact that gutter screens are recommended as part of the designing of HRW systems to reduce entry of debris and other organic matter into the systems (Lee *et al*., 2010), all the systems sampled in this current study lacked such a provision and therefore there was a direct flow of debris into the systems which could have also supported the observed increased microbial loads after the rain events in HRW systems.

Uganda is typically known for two dry and two wet seasons in a year. Although levels of *E. coli* were not significantly influenced by season, the levels of faecal enterococci were significantly ($P<0.05$) affected by season. In wet seasons, levels of feacal enterococci were higher than in dry seasons. The current results are in concordance with previous studies (Simmons *et al*., 2001; Evans *et al*., 2006, Sazakli *et al*., 2007) in which season and weather conditions also influenced the number of microorganisms. The increased levels of faecal enterococci can be explained by accumulation of debris (leaves), bird droppings, dust and other contaminants onto the collection roofs during the antecedent dry season. It was clear that the levels of indicator organisms were highest at the beginning of the rainy season and the levels gradually fall through the season with minimum levels during the dry season. This is supported by the number of rainfall events in a month which was another factor with a significant effect on the levels of faecal enterococci. Systems that received 12-18 events of rainfall in a month had significantly ($p<0.01$) higher levels of faecal enterococci than those which received less than 12 rainfall events or more than 18 events. Very few events of rain in a month is an indicator of a dry season with sunlight and a high temperature disinfection effect or a sign of less materials being washed into the tank. Many rainfall events are an an indicator of frequent washing (cleaning) of a collection roof which means minimal accumulation of debris (leaves), bird droppings, dust and other contaminants onto the collection roofs to be washed into the tanks.

Systems that lacked proper functioning taps had very high contamination levels. Lack of proper functioning taps prompted use of different materials for example pieces of wood, polythenes, maize combs etc to avoid the escape of water. Although the majority of the systems were designed in a way that they were above the ground, those tanks which were below the ground had a significantly higher microbial count. Systems that were below ground level, for example, catchment ponds and some concrete tanks were dominated by the use of smaller containers to get water. The introduction of such objects to close systems or to get water, were probably directly introducing microbes into the systems, hence causing the high levels of contamination.

The use of systems by large households and sharing also showed very high relationship with contamination of HRW. In a study carried out in Luwero district-Uganda, household size did not significantly correlate with knowledge about physical and non physical features which contribute to water quality and safety of HRW(Baguma *et al.* (2010b)). Harvested rainwater stystems used by large households and those shared by different households were more contaminated than those used by smaller households or those used by individual households without any sharing. This suggests that the more people using a system, the more microbes that are introduced. Also in such systems, maintaince is nomally poor as there could be minimal sense of ownership (Baguma *et al*., 2010) and as a result, the systems end up accumulating microbes. This agrees very well with the fact that systems that lacked first rain flush out or any form of cleaning also showed greater levels of microbes compared to those that were cleaned before the rain season. Current results agree with findings of Karim (2010) where HRW systems that were communal were more contaminated probably because of a poor operation and maintenance protocol. Karim (2010) also reported that systems that were used by bigger households were more contaminated than those that were used by small households. As was found here; the systems that were used by larger households of more than 6 people were characterised by sharing of water with neighbouring households which can also be termed as communal. It was noted that a number of HRW systems that were shared by households missed proper functioning taps while others were linking which signifies the lack of proper operation and maintenance protocals.

The absence of cleaning/first rain flush out did not predict the microbial quality of HRW, possibly because of skewed sample sizes, where almost 99% of these systems were not cleaned. This emphasizes the importance and the role of cleaning gutters, tanks or first rains flush outs. Several studies have indicated that cleaning systems are one of the factors that minimize microbial loads (Sizkiel *et al.*, 2007; Karim, 2010; Radaideh *et al.*, 2009). Studies of HRW have indicated that keeping clean gutters and flushing out the first rains resulted in HRW safe for drinking without treatment (Lee *et al.*, 2012).

Stoneburner and Low-Beer (2004) emphasised the importance of education in reducing the spread of diseases,even in the presence of epidemics like AIDS, where education has contributed to a reduction in infection by up to 70% in Uganda. De Walque (2004) also reported lower chances of contracting HIV in young rural Ugandans with secondary education compared to those with no education. The importance of education was also clearly demostrated in this study. The HRW systems which were owned by households with no education or a primary level of education only had significantly ($p<0.01$) higher levels of faecal enterococci than those owned by family heads with a secondary level of education. In Makondo, about 58% of the HRW systems were owned by households whose heads of the family had no secondary education. These results are contrary to those reported by Baguma *et al.*, (2010). The author indicated that the number of years of education was not statistically significant in rural domestic rainwater management.

Numbers of *E. coli* increased with reducing volume of water in HRW system. The high levels of contamination that were associated with little water remaining in the system could be due to the effects of sedmentation of microbes and organic matter. Systems with low volumes of HRW had significantly ($p<0.01$) high numbers of *E.coli* than those that had high volumes of HRW.

The presence of vegetions near the HRW system also influenced the microbial quality of HRW. On most of the plants (vegetations) around the HRW systems of Makondo houseolds, there were birds living, as noted from the their nests. These probably dropped feacal material directly into the tanks hence introducing microbes. The debris from the sorrounding vegetation could also possibly add organic matter which can then support survival of microbes in the HRW systems. The vegetation around the roofs has been reported to provide a shade over the water collection surfaces and faecal materials, which favour longer survival of microbial faecal indicatiors (Ahmed *et al.*, 2013).

4.7. EFFECT OF SODIS ON MICROBIOLOGICAL QUALITY OF HRW

Makondo sub-parish, Lwengo-Masaka is a rural area with no formal water supply systems and the population is forced to consume untreated water directly from shallow or artesian wells. Although other treatment methods like boiling and the use of chlorine tablets (commonly known as water guard) are in place, few households can afford them since the income in this area is low. This is the main reason why SODIS using 2L bottles was introduced in this area. In this study, WHO (2011) and UNBS (2009) drinking water guidelines were followed to describe the safety of drinking water which both state that for water to be safe for drinking, *E. coli* or faecal enterococci, which were used as microbial indicators should be undetected (zero cfu) in 100ml. Therefore, water effectively treated or termed to be safe for drinking (potable) was if the levels of *E. coli* or faecal enterococci or both were below the detection limit of 1cfu/100ml (zero cfu/ 100ml). Like the Australian drinking water guidelines (ADWG, 2011), Ugandan drinking water guidelines are the same as WHO (2011) which state that the *E. coli* count should be 0 CFU/100 ml. Generally, the sample size of SODIS treated water was generally lower than raw HRW. The sample size in dry months was also generally lower and this might have affected the observed treatment efficiency. In the dry season, some households had consumed all the water due to high temperatures while others had not exposed any bottle due to a shortage of HRW. Although the disinfection efficiency through the use of SODIS varied according to season (rainy or dry months), in some months it reached 100%. In the dry season, the treatment efficiency for *E. coli* ranged from 61% to 100% while in the wet season, it ranged from 70% to 87%.

It was noted that fewer HRWs were effectively treated using *E. coli* indicator as compared to faecal enterococci. Generally the treatment efficiency for faecal enterococci was higher than that for *E. coli* and this ranged from 79% to 100% in dry seasons and 79% to 95% in wet seasons. *E. coli* is known to be more resistant to the bactericidal effects of sunlight compared to faecal enterococci (Evison, 1988; Wegelin *et al.*, 1994; Sinton *et al.*, 2002). Generally, both faecal enterococcig and *E. coli* were better eradicators during the dry months than in rainy months. This can be explained by differences in the amount of solar radiation during the different seasons. The dry season is characterised by higher levels of solar radiation than wet months and this influences the disinfection rates of bacteria by SODIS-PET technology. Inactivation of bacteria during SODIS applications is mainly due to effects of solar radiation which is propotional to sunlight intensity (Martı´n-Domı´nguez *et al.*, 2005; Amin and Han, 2009; Asiimwe *et al*, 2013; Nalwanga *et al.* 2014). Martı´n-Domı´nguez *et al.*(2005) noted reduced exposure time required for full disinfection of total coliforms and *E. coli* on sunny days than on cloudy days due to differences in the amount and intensity of solar energy. Contrary to other SODIS studies in the field, higher treatment efficiencies were achieved in the current study. In Mustafa *et al.*, (2013) only twenty per cent of the total samples met drinking water guidelines under strong sunlight weather conditions. In this study, in all dry months (strong sunlight), more than 70% of the HRW samples treated were safe according to drinking water standards. These differences were not due to differences in the turbidity of water used. Water used in these two studies was of comparable turbidity (less than 3.5NTU) and therefore this could not have been the cause of the observed differences between the two studies. The strength of solar radiation may explain the differences observed in the two studies, However, these cannot be compared and discussed since solar radiation was not measured in the present study.

The lowest treatment efficiency was noted in August 2011 and August 2012 and could be attributed to relatively high cloud cover despite being a dry month. August according to my study had relatively similar weather conditions to March. These two months are intermediate, that is not fully dry neither rainy. Athough August is termed dry, it receives reasonable amounts of rainfall when compared to other dry months and it marks the begining of the rainy season (SON). For example August 2011 received 43.3mm compared to June another dry month which received only 2.9mm. Therefore, the households had to shift from a single day SODIS bottle exposure to two days exposure. This may not have been done appropriately contributing to lower SODIS treatment efficiency observed. These findings are supported by Nalwanga et al. (2014) who concluded that the efficiency of SODIS does not depend on season but on the daily weather conditions. Under cloudy conditions, Nalwanga *et al.* (2014) and, Amin *et al.* (2014) recommended prolonged exposure time, preferebly more than two full days of exposure to achieve complete disinfection. This is more likely to have been abused by some of the studied households, a factor that could have contributed to reduced treatment efficiency during rainy months.

4.8.USE OF COMPOUND PARABOLIC COLLECTOR (CPC) AS SODIS TREATMENT ENHANCEMENT TECHNOLOGY

During CPC treatment *E. coli* was the organism of choice because it is widely used as a faecal indicator and is known to be resistant to sunlight compared to other bacteria such as *Salmonella typhi*, *Shigella flexneri*and *Pseudomonas aeruginosa* (Wegelin *et al*., 1994). Since the control and t_0 levels were not significantly different, the observed inactivation of *E. coli* in all the experiments was as a result of SODIS treatment and there was no re-growth of *E. coli* after treatment in all experiments.

Compared to other enhanced SODIS technologies for example methacrylate and PET bottles, the borosilicate glass reactor has the best transmission properties for the microbicidal UVA and UVB (Ubomba-Jaswa *et al*., 2009). A 2.5L borosilicate glass tube reactor of 2.5L volume was able to achieve full inactivation of *E. coli* K-12 under both sunny and partially sunny conditions in only 3 hour exposure (Ubomba-Jaswa *et al*., 2010). However, in this study the 25L borosilicate glass tube reactor required 6-7 hours on continously sunny days to achieve complete inactivation of the bacteria. This difference in exposure time required to achieve complete inactivation of *E. coli* can be attributed to a number of factors. The current research used a borosilicate glass tube reactor of 25L which is 10 times larger in terms of volume than that used by Ubomba-Jaswa *et al.* (2009). The diameter of the current CPC tube used was 20cm hence solar radiation had a longer path-length to traverse than in the smaller CPC tube of 5cm diameter that was used in Ubomba-Jaswa *et al.*(2009).

In this study, a wild strain of *E. coli* isolated from protected natural well water located in a heavily populated slum was used. Ubomba-Jaswa *et al.*(2009) used a laboratory strain (*E. coli* K-12). Wild strains of *E. coli* are known to be more resistant to treatment than laboratory strains like *E. coli* K-12.Therefore, these wild strains are more suitable for testing treatment efficiencies than laboratory strains (Quek and HU, 2008; Meera and Ahammed, 2008).
Comparing the current results with those of Ubomba-Jaswa *et al.* (2010) in which a 25l methacrylate reactor CPC was used, starting at similar initial concentrations of *E. coli* similar treatment times were needed to attain the levels of *E. coli* below detection limit. In the former study the well water had no dissolved suspended solids (maximum dissolved organic carbon was 5 mg l^{-1}), very low turbidity (1.5 NTU), and a bacteria from the Spanish collection of cultures was used (Ubomba-Jaswa *et al*., 2010). These collection strains have been shown to

be more sensitive to disinfection methods than wild species isolated from real contaminated water sources (Agulló-Barceló *et al.*, 2013). In the present study, the contaminated water had a complex chemical matrix, a moderate level of TDS and naturally ocurring bacteria, as explained in the experimental section (section 2.1.5).

A lower efficiency of solar disinfection for naturally contaminated waters, compared with ideal conditions of distilled water and well water spiked with culture strain (collection bacteria), was also reported with a similar design CPC-25l-solar reactor PSA in Southern Spain (Bichai *et al.*, 2012). The authors assessed the efficiency of solar disinfection to reduce microbial contamination in solar-treated natural wastewater effluents from a municipal wastewater treatment plant which was subsequently used for irrigation of horticultural crops. The authors reported a decrease from bacterial concentrations of $>10^3$-10^4*E. coli* CFU ml^{-1} to <2 CFU/ml. (detection limit of that study) within 4 hours of solar exposure of 20 liters of real wastewater effluents, using the same reactor under clear sunny conditions in the South of Spain. Furthermore, they reported that the required exposure times for disinfecting similar levels of *E. coli* in distilled water (1h), well water (1.5h) and simulated effluents of wastewater (3h) were shorter than for natural contaminated wastewaters (4h) (Bichai *et al.*, 2012).

Despite the synergistic effect of temperature and UVA that has been reported to play a key role in SODIS inactivation of bacteria (Kehoe *et al.*, 2001, Ubomba-Jaswa *et al.* 2010) this was not observed in this study. This can be explianed by the fact that the thermal inertia associated with the large volume of water is such that water temperature increases slowly during solar exposures compared with those reported for smaller volumes of up to 2.5L. None of the current experiments achieved maximum water temperatures near the 45°C that has been reported necessary for a synergistic effect (Joyce *et al.* 1996). However, since the irradiated collector surface of the 25L CPC is ~2 times that of the 2.5L CPC reactor used by Ubomba-Jaswa *et al.* (2010), a 25L CPC would require nearly 5 times longer continous solar exposure to increase to 45°C from 20°C compared to the time required for the smaller volume reactor. Consequently, given the disparity/differences between volume and illuminated area, it is not surprising that the maximum water temperature achieved at any point in the studies was only 38°C (December 2011) for the 25L reactor.

Total dissolved solids are reported to have an effect on bacterial inactivation for several SODIS enhancement reactors (Kehoe *et al.*, 2001). Curtis *et al.* (1992) suggested that natural organic matter may facilitate faster solar disinfection as it acts as a photo-sensitizer. Ubomba-Jaswa *et al.* (2009) also noted that the higher the turbidity, the higher the maximum water temperature attained since the organic matter absorbs heat (Kehoe *et al.*, 2001). On the other hand, increased turbidity was indicated to reduce solar light penetration (Joyce *et al.*, 1996, Kehoe *et al.*, 2001) which is very important in treating microbes in water. Therefore, the advantage of increased temperature as a result of increased turbidity to facilitate increased synergicistic effect between UVA and temperature to inactivate bacteria is thus not enough to compensate for the reduction of solar penetration through turbid water (Kehoe *et al.*, 2001).

5 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Harvesting rainwater is widely practiced in the Makondo area. The water is used for farming and also for drinking.

Water sampled from HRW systems in the Makondo area did not comply with microbiological standards for drinking water and so the water should always be treated before drinking.

SODIS was shown to be an effective method for treating the HRW. On sunny days, 2L bottles should be exposed for a minimum of 7 hours, however, when conditions are cloudy bottles should be exposed for two complete days to ensure total disinfection.

The microbial quality of the HRW could be improved by considering proper construction and siting of the tank, enhancing the method of abstraction of the water and attention to cleaning the HRW system.

The use of CPC SODIS reactor technology is suitable for treating drinking water both at household level and institutional level in Sub-Saharan Africa and other similar tropical climates if careful consideration of the cloud cover and rainfall is taken into account.

Recommendations

- ❑ For safety reasons the HRW should first be treated before drinking

- To minimise contamination levels in HRW cleaning tanks, flushing out the remaining water towards the beginning of the rainy season in addition to flushing out the first rain event, are necessary actions.
- Water should be abstracted using proper functioning taps, overhanging vegetation should be avoided, a proper draining water collection area should be maintained in addition to educating people (children) in rural areas the necessary actions to minimise on contamination levels in HRW.
- Bottles to be used the following day should be put in the sun the day before consumption to ensure adequate time for treatment of the water.
- Community health extension workers should also include training on maintaining good sanitary conditions for HRW systems and SODIS treatment procedures in their sessions.
- The CPC should be installed at community centres such as schools and health centres for people to access safe drinking water at these points.

6 SUGGESTIONS FOR FUTURE WORK

- A study to access microbial pathogens in HRW in Makondo-Masaka should be done
- A study is required to access the factors influencing the adaptability of SODIS use in Makondo-Masaka

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Appendix 1: Ethical approval from RCSI

Royal College of Surgeons in Ireland
The Research Ethics Committee
121 St. Stephens Green, Dublin 2, Ireland
Tel: +353 1 4022373 Fax: +353 1 4022449 Email: recadmin@rcsi.ie

Dr. David Smith, Acting Chair
Ms. Stephanie O'Connor, Convenor

Royal College of Surgeons in Ireland

RCSI

17th December, 2010

Miss Rosemary Nalwanga,
Makerere University
C/o Dr. Kevin McGuigan,
Department of Physiology,
Royal College of Surgeons in Ireland,
121 St. Stephen's Green,
Dublin 2.

Ethics Reference No:	REC584
Project Title:	An evaluation of SODIS enhancement technologies on treating rain harvested water
Researchers Name:	Miss Rosemary Nalwanga
Other individuals involved:	Dr Kevin G McGuigan, RCSI Dr. Brid Quilty, DCU Dr. Charles K. Musanja, Makerere University

Dear Miss Rosemary Nalwanga,
Thank you for your Research Ethics Committee (REC) application.

We are pleased to advise that ethical approval has been granted by the committee for this study.

This letter provides approval for data collection for the time requested in your application and for an additional 6 months. This is to allow for any unexpected delays in proceeding with data collection. Therefore this research ethics approval will expire on **31st July, 2013.**

Where data collection is necessary beyond this point, approval for an extension must be sought from the Research Ethics Committee.

This ethical approval is given on the understanding that:

- All personnel listed in the approved application have read, understand and are thoroughly familiar with all aspects of the study.
- Any significant change which occurs in connection with this study and/or which may alter its ethical consideration, must be reported immediately to the REC, and an ethical amendment submitted where appropriate.

We wish you all the best with your research.

Yours sincerely,

PP Ms. Stephanie O'Connor (Convenor)
Dr David Smith (Acting Chair)

200 RCSI
1810–2010

Appendix 2: Participant Consent Form

Study Title: AN EVALUATION OF THE SODIS ENHANCEMENT TECHNOLOGIES FOR TREATING RAIN HARVESTED WATER

Name: .... Code…………………………..
Address: ....
....
....
....

1. I agree to participate in this research
2. This agreement is of my own free will
3. I have had the opportunity to ask any questions about the study and all my questions have been satisfactorily answered
4. I have been given full information regarding the aims of the research and have been given information with the Researcher's names on and a contact number and address if I require further information.
5. All personal information provided by myself will remain confidential and no information that identifies me will be made publically available
6. There are no risks involved in the participation of this study

I have read and understood the above, and give consent to participate

Signed: .... Date: .... (*by participant*)
Print name: ....

DECLARATION BY THE INVESTIGATOR:
I confirm that I have provided an information sheet and explained the nature and effect of the procedures to the participant and that his/her consent has been given freely and voluntarily

Signed by researcher
Signed: .... Date: ....
Print Name: ....
Research Code....................................
1 copy to participant and the other 1 copy for researcher

Appendix 3: Participant information sheet

Research Title: <u>An evaluation of the SODIS enhancement technologies for treating rain harvested water</u>

My name is **Nalwanga Rosemary.** I am a researcher working at Makerere University, Department of Food Science and Technology. We are working on a project looking at a household water treatment technology which utilises solar energy to disinfect drinking water (Solar Water Disinfection-SODIS). The overall objective of this research is to develop a sustainable, feasible and affordable household water treatment method so as to improve on accessibility of safe drinking water and thus improve on people's health conditions. We are talking to a number of households about their experiences of using rain harvested water for drinking purposes.

What will I have to do if I take part?

If you agree to take part, we will ask you to allow us sample your rain water harvesting system for example a tank, catchment pond, drum or pots on a monthly basis for one year. Also, we will request you to use SODIS technology so that in the future you will be able to help us and answer some questions. The materials for SODIS use like PET bottles will be provided. There will be no any right or wrong answers – we will just want to hear about your opinions. The discussion will take about an hour at the longest. Please note that some of the questions will relate to your personal history and experiences on using different drinking water treatment methods.

Do I have to take part?

No! Your participation in the study is **completely voluntary.** If you don't want to take part, you do not have to give a reason and no pressure will be out on you to try and change your mind. You can pull out of the study at any time. If you refuse to participate now, or withdraw from the study later, you will **not** be affected in any way.

If I agree to take part what happens to what I say?

Any personal information used in this study will be treated **confidentially**. The data will be collected and stored in accordance with the Data Protection Act 1998 and will be disposed of in a secure manner. Information which identifies you as an individual will not be released, without your consent, to anyone for purposes which are not directly related to this research study.

What do I do now?

Think about the information on this sheet, and ask me if you are not sure about anything. If you agree to take part, sign the consent form. The consent form will not be used to identify you. It will be filed separately from all other information. If, after the discussion, you want any more information about the study, please feel free to let me know or to contact me through the address given below.

You will be given a copy of this statement, which serves to acknowledge the fact that you have been informed about the project and that you have voluntarily agreed to participate.
The contact details for the Researcher:

Name: Nalwanga Rosemary
Tel No.: +256 (0) 782-573757
Email: nalwangarose@yahoo.com

THANK YOU VERY MUCH FOR YOUR HELP!

Appendix 4: Questionnaire Designed to Check the Awareness Level Regarding the SODIS (Solar Water Disinfection) Technique

Purpose of survey: This survey is for academic purpose.
Name of the project: Water is Life " Amazzi Bulamu"

Name of respondent: ______________________ Date: ______________
Address: ______________________ Mob No: ______________

WATER INFORMATION

1. What is the source of your drinking water?

(a) Un protected well (b) protected well (c) hand pump (d) Harvested rain water
(e) Any other ____________

2. Do you feel that the water you are using is safe for drinking purposes
   (a) Yes (b) No (c) Do not know

If no, then

(i) Water is turbid (ii) Bad odour (iii) Doesn't taste good
(iv) Any other (Please specify) ____________

3. Do you use any method to treat / purify drinking water?
   (a) Yes (b) No (c) Do not know

If yes, then is it?

(i) SODIS (Solar water Disinfection) (ii) Boiling (iii) Chlorination (IV) Filtration (v) Water guard

4. How much does it cost you per week to treat/purify? ________________

HEALTH INFORMATION

5. Which of the following diseases do you commonly get?

(a) Diarrhoea (b) Gastro-trouble (c) Cholera (d) Dysentery
(e) Typhoid (f) any other (Please specify) ____________________

6. How often do you get ill?

Once in a week (b) once in 2 weeks (c) Once in a month (d) once in 6 months (d) once in a year (e) any other, please specify ____________

7. To whom do you consult in case you are ill?
   (a) Clinic (b) buy medicine from Pharmacy (c) Doctor (d) use traditional drugs

(e) Any other, please specify ____________

SODIS (SOLAR WATER DISINFECTION) TECHNIQUE INFORMATION

8. Have you ever been consulted regarding the awareness of safe drinking water before?

a. Yes b. No

If Yes, then by whom
(i) Government officials (ii) NGOs (iii) Private Agencies (iv) Students/ Volunteers (v) Any other (Please specify) ________________

9. Do you know about SODIS (Solar water Disinfection) technique?

(a) Yes (b) No

If Yes, then how
(i) School/ College (ii) Media (iii) Friends/ Colleagues
(iv) Any other (Please specify) ___________________

10. Could you please explain SODIS to me?

0 (No knowledge; **criteria:** has never heard about SODIS)
0.1 (Very little knowledge; **criteria:** has heard about SODIS but does not know how to prepare it and that SODIS disinfects water)
0.3 (Some knowledge; **criteria:** knows in principle how to prepare SODIS and that it disinfects water but does not know why or gives some "magic" explanation)
0.6 (Good knowledge; **criteria:** knows how to prepare SODIS, and either the sun or the temperature as the cause of the disinfection process is mentioned)
1 (Very good knowledge- **criteria:** complete understanding of how to do SODIS and how it works)

11. Are the transparent plastic bottles available at your house?

(a) Yes (b) No (c) I will manage to buy

12. For how long in a day do u receive sunlight at your home?

(a) ½ day (b) the all day (c) Any other (Please specify) ___________________

13. Are you willing to attend the SODIS (Solar water Disinfection) Workshop?

(a) Yes (b) No
If No, then why
(i) Not interested (ii) Lack of time (iii) Far from house
(iv) Boring (v) Any other (Please specify) __________________

RAIN WATER HARVESTING (RWH) INFORMATION

14. Do you harvest rainwater?

(a) Yes (b) No

If yes, what do u use it for?

(i) Drinking (ii) washing clothes (iii) watering animals
(i) Any other purpose (Please specify) __________________
If no, what is the reason?
(i) Its expensive (ii) Bad water quality (iii) consumes time

(i) Any other reason (Please specify) ________________

15. Have you heard of rain water harvest before?

(a) Yes (b) No

If yes, from where?

(i) Friend (ii) work shop (iii) School

(iv) Any other reason (Please specify) ________________

16. If used for drinking, do u treat / purify it?

(a) Yes (b) No

If Yes, then is it?

(j) SODIS (Solar water Disinfection) (ii) Boiling (iii) Chlorination (IV) Filtration (v) Water guard

17. In which container do you store rainwater?

(a) Metallic drums (b) Jerrycans of 20 liters (c) Crest PVC tanks

(d) Built concrete tanks (c) Any other (Please specify) ________________

18. How do you collect it from the storage container?

(a) Tap and gravity (b) use a smaller container (c) Pump

(d) Siphoning (d) any other (Please specify) ________________

19. Do you think harvesting rainwater is a good mitigation practice to water scarcity in this time of climatic change?

(a) Yes (b) No

COST AND SOCIAL ASPECTS

20. How much did you spend to get the storage tank (Ug shs)________________

21. How much time do you save in a day when you use stored rain water (by not fetching from other sources) ________________

22. What do you use this time for?

(a) farming (b) visiting friends (c) resting at home (d) Any other (Please specify) ________________

23. How many Jerrycans do you use a day? ________________

FAMILY INFORMATION

24. How many members do u have in your family________________

25. What is the highest education level of your family

(a) No school (b) Primary (c) Secondary (d) Higher secondary or more

26. Monthly income (Ug shs) ______________

27. Any suggestion(s):

i. ________________________________

ii. ________________________________

Appendix 5: Harvesting rain water system sanitary inspection form

Rainwater Collection and Storage Sanitary inspection and Survey Form

HH code________________________ Date of inspection: ______________

Risk Assessment

1. Is there roaming domestic animals/birds at the Household or neighborhood? Y / N
2. Is there overhanging trees/vegetation around the system? Y / N
3. Is there a pit latrine in less than 15m away from the system? Y / N
4. Is water abstracted by use of a smaller container hanging on a rope or stick? Y / N
5. Is the tap (outlet) defective or leaking? Y / N
6. Are the guttering channels that collect water dirty or mal functioning? Y / N
7. Does the system have an entry points or linkages (not well closed)? Y / N
8. Is the water collection area poorly drained? Y / N
9. Is the tank used by more than one household? Y / N
10. Is there no cleaning of system before the next rain season? Y / N

Total score (no. of yes): ________/10_____

Comments

No. of people in a household(s) using a system...................

The highest level of education for the head of family............

Size (volume of a system)...

Comment on rain gauges: In good condition (yes/NO)

Appendix 6: Variation of temperature in the different harvesting rainwater collection systems

Month/Year		Temp. of Raw Harvested Rain water (HRW)			
Aug. 2011	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (5)	22.2(±0.71)	22.2	21.4	23.0
	Concrete (10)	22.2(±1.3)	22.6	20.1	24.6
	Metallic (16)	22.2(±0.8)	22.0	20.7	23.5
	Plastic (10)	22.2(±0.5)	22.5	21.5	23.2
	Overall (41)	**22.4(±0.9)**	**22.3**	**20.1**	**24.6**
Sept. 2011	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (6)	23.1(±0.8)	23.3	21.6	24.0
	Concrete (11)	23.5(±1.5)	23.2	21.8	26.8
	Metallic (18)	23.7(±1.5)	23.5	20.7	26.9
	Plastic (9)	24.2(±1.1)	23.8	22.3	25.9
	Overall (44)	**23.7(±1.4)**	**23.5**	**20.7**	**26.9**
Oct. 2011	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (8)	22(±0.5)	22.1	20.9	22.5
	Concrete (9)	24.2(±2.5)	23.0	21.4	27.8
	Metallic (16)	22.3(±1.5)	22.0	19.5	25.4
	Plastic (11)	23.9(±2.4)	23.2	21.3	28.6
	Overall (44)	**23.0(±2.1)**	**22.3**	**19.5**	**28.6**
Nov. 2011	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (8)	23.3(±1.6)	23.0	20.7	26.1
	Concrete (10)	21.8(±0.9)	21.8	20.3	23.5
	Metallic (18)	22.4(±1.6)	22.8	19.7	25.5
	Plastic (11)	23.4(±1.4)	22.9	22.0	26.2
	Overall (47)	**22.6(±1.5)**	**22.7**	**19.7**	**26.2**
Dec. 2011	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (8)	24.1(±1.7)	24.0	21.3	26.7
	Concrete (11)	23.6(±1.8)	23.5	21.0	27.0
	Metallic (18)	23.3(±1.3)	23.5	21.4	25.5
	Plastic (11)	25.0(±3.4)	25.0	20.9	33.6
	Overall (48)	**23.9(±2.2)**	**23.7**	**20.9**	**33.6**
Jan. 2012	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (6)	24.6(±1.4)	24.7	23.0	26.1
	Concrete (10)	24.2(±1.8)	23.7	21.9	26.7
	Metallic (13)	23.8(±1.8)	24.1	20.7	26.2
	Plastic (11)	24.9(±1.1)	25.1	23.0	27.2
	Overall (40)	**24.3(±1.6)**	**24.5**	**20.7**	**27.2**

Feb. 2012	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (1)	28.0(±N/A)	28.0	28.0	28.0
	Concrete (4)	25.1(±2.1)	24.5	23.3	28.0
	Metallic (8)	27.2(±2.5)	27.0	24.0	31.0
	Plastic (6)	27.3(±2.9)	27.5	24.0	31.0
	Overall (19)	**26.8(±2.5)**	**27.0**	**23.3**	**31.0**
Mar. 2012	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (2)	25.2(±1.3)	24.5	24.3	26.7
	Concrete (11)	24.7(±1.4)	24.6	22.5	27.3
	Metallic (8)	24.2(±1.5)	24.8	21.3	25.7
	Plastic (9)	25.0(±2.9)	25.4	19.5	28.6
	Overall (30)	**24.7(±2.0)**	**24.8**	**19.5**	**28.6**
Apr. 2012	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (8)	26.7(±1.8)	26.9	23.6	29.0
	Concrete (9)	24.9(+2.4)	25.0	22.4	30.0
	Metallic (17)	25.3(±3.4)	24.0	20.0	33.6
	Plastic (9)	26.1(±2.8)	25.0	24.0	32.0
	Overall (43)	**25.6(±2.8)**	**24.5**	**20.0**	**33.6**
Jun. 2012	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (6)	26.0(±1.3)	25.5	25.0	28.0
	Concrete (9)	24.9(±1.5)	25.0	23.0	27.0
	Metallic (15)	26.5(±2.1)	27.0	22.3	29.0
	Plastic (8)	25.8(±0.9)	26.0	24.0	27.0
	Overall (38)	**25.9(±1.7)**	**26.0**	**22.3**	**29.0**
Jul. 2012	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (1)	27.0(±N/A)	27.0	27.0	27.0
	Concrete (8)	25.1(±0.7)	25.0	24.0	26.0
	Metallic (9)	26.6(±2.3)	26.3	23.0	30.0
	Plastic (10)	25.8(±1.6)	25.4	24.0	29.0
	Overall (28)	**25.9(±1.7)**	**25.8**	**23.0**	**30.0**
Aug. 2012	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (8)	24.2(±1.7)	24.0	22.3	26.5
	Concrete (8)	24.5(±1.4)	24.5	22.6	26.7
	Metallic (15)	25.4(±1.8)	25.4	23.0	31.0
	Plastic (10)	25.1(±1.5)	24.6	23.4	28.6
	Overall (41)	**25.0(±1.7)**	**24.8**	**22.3**	**31.0**

Appendix 7: Varriation of pH in raw harvested rain water

Month/Year		pH of Raw Harvested Rain water (HRW)			
Aug. 2011	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (5)	8.0(±1.1)	7.4	7.1	9.4
	Concrete (10)	8.1(±1.3)	7.7	6.0	9.7
	Metallic (16)	7.7(±1.1)	7.2	6.7	9.6
	Plastic (10)	7.5(+1.0)	7.3	6.1	9.9
	Overall (41)	**7.8(±1.1)**	**7.4**	**6.0**	**9.9**
Sept. 2011	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (6)	8.4(±1.1)	8.4	6.8	9.7
	Concrete (11)	8.5(±0.9)	8.9	6.8	9.9
	Metallic (18)	7.7(±1.1)	7.7	6.0	9.9
	Plastic (9)	7.9(±1.3)	7.9	6.3	10.1
	Overall (44)	**8.1(±1.1)**	**8.0**	**6.0**	**10.1**
Oct. 2011	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (8)	7.3(±1.3)	7.0	6.1	10.4
	Concrete (9)	7.2(+0.4)	7.4	6.2	7.7
	Metallic (16)	7.3(±0.6)	7.5	5.7	8.0
	Plastic (11)	6.9(±0.7)	6.9	5.3	8.0
	Overall (44)	**7.2(±0.7)**	**7.2**	**5.3**	**10.4**
Nov. 2011	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (8)	6.9(±1.2)	6.6	5.2	9.2
	Concrete (10)	7.5(±1.3)	7.6	9.6	9.7
	Metallic (18)	7.0(±1.4)	7.0	4.8	10.8
	Plastic (11)	6.1(±1.2)	5.8	5.0	9.6
	Overall (47)	**6.9(±1.4)**	**6.7**	**4.8**	**10.8**
Dec. 2011	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (8)	7.5(±1.3)	7.0	6.7	10.7
	Concrete (11)	7.8(±1.0)	7.7	5.6	9.8
	Metallic (18)	7.1(±0.7)	7.1	6.0	8.0
	Plastic (11)	7.0(±0.7)	7.0	5.8	8.1
	Overall (48)	**7.3(±0.9)**	**7.2**	**5.8**	**10.7**
Jan. 2012	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (6)	6.6(±0.1)	6.7	6.5	6.8
	Concrete (10)	7.4(±0.7)	7.6	6.5	8.4
	Metallic (13)	6.9(±0.7)	6.8	6.2	8.9
	Plastic (11)	6.8(±0.3)	6.7	6.4	7.5
	Overall (40)	**7.0(±0.6)**	**6.7**	**6.2**	**8.9**
Feb. 2012	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (1)	6.6(±N/A)	6.6	6.6	6.6
	Concrete (4)	7.5(±0.8)	7.6	6.5	8.4
	Metallic (8)	6.6(±0.4)	6.5	6.0	7.4
	Plastic (6)	6.3(±0.4)	6.5	5.5	6.7
	Overall (19)	**6.8(±0.7)**	**6.5**	**5.5**	**8.4**

Mar. 2012	HRW system	Mean	Median	Min	Max
	Catchment (2)	6.7(±0.5)	6.7	6.3	7.0
	Concrete (11)	7.0(±0.7)	6.8	6.3	8.8
	Metallic (8)	6.3(±0.8)	6.2	5.3	7.7
	Plastic (9)	6.3(±0.7)	6.5	5.2	7.2
	Overall (30)	**6.6(±0.7)**	**6.6**	**5.2**	**8.8**
Apr. 2012	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (8)	6.8(±0.5)	6.7	6.2	7.5
	Concrete (9)	6.9(±0.4)	6.9	6.3	7.4
	Metallic (17)	6.7(+0.5)	6.8	5.9	7.5
	Plastic (9)	6.8(±0.7)	6.6	6.0	8.1
	Overall (43)	**6.8(±0.5)**	**6.7**	**5.9**	**8.1**
Jun. 2012	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (6)	6.3(±0.3)	6.4	5.7	6.5
	Concrete (9)	6.7(±0.4)	6.6	6.1	7.7
	Metallic (15)	6.7(±0.5)	6.5	6.0	7.8
	Plastic (8)	6.4(±0.7)	6.4	5.5	7.4
	Overall (38)	**6.5(±0.5)**	**6.5**	**5.5**	**7.8**
Jul. 2012	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (1)	7(±N/A)	7.3	7.3	7.3
	Concrete (8)	7.2(±2.2)	7.2	6.5	7.9
	Metallic (9)	6.3(±1.9)	6.0	5.5	7.3
	Plastic (10)	6.6(±0.4)	6.5	5.9	7.0
	Overall (28)	**6.6(±0.6)**	**6.6**	**5.5**	**7.9**
Aug. 2012	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (8)	7.5(±0.6)	7.4	6.8	8.4
	Concrete (8)	7.5(±0.8)	7.7	6.0	8.6
	Metallic (15)	6.9(±0.8)	7.1	5.3	8.1
	Plastic (10)	7.3(±0.9)	7.1	5.5	8.5
	Overall (41)	**7.2(±0.8)**	**7.3**	**5.3**	**8.6**

Appendix 8: Variation of TDS in raw harvested rainwater

Month/Year		TDS [mg/l] of Raw Harvested Rain wa (HRW)			
Aug. 2011	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (5)	87.0(±86.3)	47.0	28.0	237.0
	Concrete (10)	45.5(±26.6)	39.0	21.0	100.0
	Metallic (16)	27.2(±10.0)	25.5	13.0	54.0
	Plastic (10)	19.3(±3.5)	20.0	14.0	24.0
	Overall (41)	**37.0(±37.3)**	**25.0**	**13.0**	**237.0**
Sept. 2011	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (6)	18.7(±15.7)	16.5	2.0	48.0
	Concrete (11)	18.5(±11.8)	13.0	5.0	39.0
	Metallic (18)	14.9(±12.5)	9.9	6.0	55.0
	Plastic (9)	14.6(±11.8)	11.0	2.0	43.0
	Overall (44)	**16.2(±12.3)**	**12.0**	**2.0**	**55.0**
Oct. 2011	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (8)	54.4(±46.9)	38.5	5.0	141.0
	Concrete (9)	39(±74.9)	8.0	6.0	237.0
	Metallic (16)	21.6(±18.6)	14.0	7.0	76.0
	Plastic (11)	17.3(±27.5)	9.0	6.0	100.0
	Overall (44)	**30.0(±43.5)**	**12.0**	**5.0**	**237.0**
Nov. 2011	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (8)	37.3(±29.7)	23.5	9.0	85.0
	Concrete (10)	25 (±16.3)	24.0	6.0	60.0
	Metallic (18)	28.7(±29.1)	19.5	6.0	125.0
	Plastic (11)	45.6(±56.0)	13.0	0.0	193.0
	Overall (47)	**33.3(±35.2)**	**22.0**	**0.0**	**193.0**
Dec. 2011	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (8)	48.5(±34.8)	59.5	6.0	95.0
	Concrete (11)	14.2(±10.4)	12.0	5.0	26.0
	Metallic (18)	11.2(±10.4)	9.0	5.0	40.0
	Plastic (11)	18(±12.8)	12.0	6.0	43.0
	Overall (48)	**19.7(±20.9)**	**10.5**	**5.0**	**95.0**
Jan. 2012	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (6)	77(±25.7)	83.5	37.0	105.0
	Concrete (10)	42(±27.1)	27.0	15.0	89.0
	Metallic (13)	40.5(±27.1)	34.0	11.0	89.0
	Plastic (11)	24.7(±13.1)	20.0	11.0	48.0
	Overall (40)	**42.0(±28.2)**	**32.0**	**11.0**	**105.0**
Feb. 2012	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (1)	50(±N/A)	50.0	50.0	50.0
	Concrete (4)	58(±37.4)	46.5	30.0	109.0
	Metallic (8)	16.1(±16.7)	8.0	6.0	52.0
	Plastic (6)	6.3(±2.1)	6.0	4.0	10.0
	Overall (19)	**24.6(±27.7)**	**8.0**	**4.0**	**109.0**

Mar. 2012	HRW system	Mean	Median	Min	Max
	Catchment (2)	167.5(±58.7)	167.5	126.0	209.0
	Concrete (11)	52.3(±82.0)	17.0	8.0	287.0
	Metallic (8)	35.1(±58.4)	13.5	2.0	175.0
	Plastic (9)	17.4(±13.8)	10.0	6.0	41.0
	Overall (30)	**44.9(±68.0)**	**15.5**	**2.0**	**287.0**
Apr. 2012	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (8)	64.6(±46.0)	65.5	9.0	136.0
	Concrete (9)	35.7(±23.6)	35.0	6.0	72.0
	Metallic (17)	31.8(±29.8)	15.0	6.0	107.0
	Plastic (9)	49.7(±33.4)	47.0	9.0	109.0
	Overall (43)	**42.5(±34.2)**	**28.5**	**6.0**	**136.0**
Jun. 2012	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (6)	59.2(±47.0)	49.0	11.0	142.0
	Concrete (9)	53.3(±46.3)	36.0	10.0	150.0
	Metallic (15)	79.9(±53.0)	73.0	12.0	186.0
	Plastic (8)	31.5(±14.7)	30.0	7.0	52.0
	Overall (38)	**62.2(±48.0)**	**45.0**	**7.0**	**186.0**
Jul. 2012	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (1)	254.0(±N/A)	254.0	254.0	254.0
	Concrete (8)	37.8(±37.8)	56.5	7.0	110.0
	Metallic (9)	36.7(±31.0)	25.0	5.0	98.0
	Plastic (10)	63.9(±61.2)	44.0	8.0	181.0
	Overall (28)	**60.0(±59.1)**	**43.0**	**5.0**	**254.0**
Aug. 2012	**HRW system**	**Mean**	**Median**	**Min**	**Max**
	Catchment (8)	64.3(±36.9)	78.0	7.0	107.0
	Concrete (8)	34.6(±29.7)	22.5	9.0	92.0
	Metallic (15)	27.2(±51)	9.0	4.0	206.0
	Plastic (10)	10.5(±6.4)	9.0	4.0	25.0
	Overall (41)	**40(±40.0)**	**11.0**	**4.0**	**206.0**

Appendix 9: ***E. coli*** **contamination levels (CFU/100ml) in raw HRW systems and SODIS treated water during the different months of the year**

MONTH/ YEAR	**HRW system**	**Sample size (n)**		***Mean***		***Median***		***Range***	
Aug.2011		**Raw**	**Treated**	**Raw**	**Treated**	**Raw II**	**Treated**	**Raw**	**Treated**
	Catchment	5	4	114(±162)	7(± 13)	68	1	9->400	0-27
	Concrete	10	9	46 (± 125)	3(± 8)	2	0	0->400	0-24
	Metallic	16	17	104(±177)	1(±1)	2	0	0->400	0-1
	Plastic	10	10	128 (± 188)	1(± 3)	19	0	0->400	0-10
	Overall	**41**	**40**	**97(±163)**	2(±7)	**5**	0	**0->400**	0-27
Sept.2011	**HRW system**	**n-raw**	***n-treated***	***Mean-raw***	***mean-treated***	***Median-raw***	***median-treated***	***Range-raw***	***Range-treated***
	Catchment	6	6	100 (± 154)	2(± 5)	30	0	0->400	0-13
	Concrete	11	10	88 (± 155)	1(± 3)	23	0	0->400	0-6
	Metallic	18	18	139 (± 191)	1(± 4)	7	0	0->400	0-15
	Plastic	9	10	92 (± 175)	0(±0)	0	0	0->400	0-0
	Overall	**44**	**44**	**111(±170)**	1(±3)	**15**	0	**0->400**	0-15
Oct.2011	**HRW system**	**n-raw**	***n-treated***	***Mean-raw***	***mean-treated***	***Median-raw***	***median-treated***	***Range-raw***	***Range-treated***
	Catchment	8	8	52 (±141)	0(±0)	1	0	0->400	0-0
	Concrete	9	9	9 (±15)	1(±1)	2	0	0->46	0-4
	Metallic	16	16	58 (±135)	1(± 1)	1	0	0->400	0-2
	Plastic	11	11	46 (±119)	1(±3)	2	0	0->400	0-9
	Overall	**44**	**44**	**44(±115)**	1(±2)	**2**	0	**0->400**	0-9

Nov.2011	**HRW system**	**n-raw**	***n-treated***	***Mean-raw***	***mean-treated***	***Median-raw***	***median-treated***	***Range-raw***	***Range-treated***
	Catchment	8	8	111(±180)	1(±1)	9	0	0->400	0-1
	Concrete	10	10	48 (±124)	1(±)1	5	0	0->46	0-3
	Metallic	18	18	56 (± 126)	1(±3)	7	0	0->400	0-3
	Plastic	11	11	43 (± 120)	1(±1)	0	0	0->400	0-9
	Overall	**47**	**47**	**61(±132)**	1(±2)	**3**	0	**0->400**	0-9
Dec. 2011	**HRW system**	**n-raw**	***n-treated***	***Mean-raw***	***mean-treated***	***Median-raw***	***median-treated***	***Range-raw***	***Range-treated***
	Catchment	8	8	62 (±137)	0(±3)	11	0	0->400	0-0
	Concrete	11	11	9 (± 13)	1(±0)	1	0	0-42	0-5
	Metallic	18	18	26 (± 94)	1(±2)	1	0	0->400	0-17
	Plastic	11	11	8 (±24)	0(±5)	0	0	0-80	0-0
	Overall	**48**	**48**	**24(±81)**	1(±3)	**1**	0	**0->400**	0-17
Jan. 2012	**HRW system**	**n-raw**	***n-treated***	***Mean-raw***	***mean-treated***	***Median-raw***	***median-treated***	***Range-raw***	***Range-treated***
	Catchment	6	6	19(±192)	19(±45)	73	0	0->400	0-110
	Concrete	10	10	0 (± 124)	1(± 1)	24	0	0-42	0-1
	Metallic	13	13	0 (±110)	0(±0)	9	0	0->400	0-0
	Plastic	11	11	1 (±9)	0(±0)	1	0	0-26	0-0
	Overall	**40**	**40**	**60(±120)**	3(±17)	**9**	0	**0->400**	0-110

Feb. 2012	**HRW system**	**n-raw**	***n-treated***	***Mean-raw***	***mean-treated***	***Median-raw***	***median-treated***	***Range-raw***	***Range-treated***
	Catchment	1	1	0 (± N/A)	0(±N/A)	0	0	0->400	0-0
	Concrete	4	4	120 (±190)	0(±0)	40	0	0->46	0-0
	Metallic	8	9	3 (± 8)	0(±0)	0	0	0-23	0-0
	Plastic	6	6	0 (±1)	0(±0)	0	0	0->1	0-0
	Overall	**19**	**20**	**27(±92)**	0(±0)	**0**	0	**0->400**	0-0
Mar.2012	**HRW system**	**n-raw**	***n-treated***	***Mean-raw***	***mean-treated***	***Median-raw***	***median-treated***	***Range-raw***	***Range-treated***
	Catchment	2	2	116 (±0)	0(± 0)	116	0	116	0-0
	Concrete	11	11	62 (± 110)	1(±1)	6	0	0->400	0-3
	Metallic	8	8	53 (± 143)	1(± 3)	0	0	0->26	0-8
	Plastic	9	9	6 (±11)	0(± 0)	0	0	0-28	0-0
	Overall	**30**	**30**	**46(±100)**	1(±2)	**2**	0	**0->400**	0-8
Apr.2012	**HRW system**	**n-raw**	***n-treated***	***Mean-raw***	***mean-treated***	***Median-raw***	***median-treated***	***Range-raw***	***Range-treated***
	Catchment	8	8	154 (±208)	23(± 64)	82	0	12->400	0-181
	Concrete	9	9	75 (± 130)	1(±1)	17	0	0-379	0-1
	Metallic	17	17	32 (±60)	1(±4)	10	0	0-198	0-15
	Plastic	9	9	27 (±31)	1(±1)	5	0	0-77	0-1
	Overall	**43**	**43**	**62(±97)**	5(±28)	**6**	0	**0->400**	0-181

June. 2012	HRW system	n-raw	*n-treated*	*Mean-raw*	*mean-treated*	*Median-raw*	*median-treated*	*Range-raw*	*Range-treated*
	Catchment	6	6	31 (± 37)	0(±0)	17	0	0->400	0-0
	Concrete	9	9	109 (+157)	3(±8)	4	0	0->46	0-25
	Metallic	15	15	112 (±148)	3(± 7)	62	0	0->400	0-26
	Plastic	8	8	6 (± 8)	1(±1)	3	0	0->400	0-1
	Overall	**38**	**38**	**75(±123)**	2(±6)	**14**	0	**0->400**	0-26
July. 2012	**HRW system**	**n-raw**	***n-treated***	***Mean-raw***	***mean-treated***	***Median-raw***	***median-treated***	***Range-raw***	***Range-treated***
	Catchment	1	1	148 (±N/A)	0(± N/A)	148	0	148-148	0-0
	Concrete	8	8	80 (±151)	8(± 16)	11	0	0->400	0-43
	Metallic	9	9	36 (± 66)	0(±0)	5	0	0-175	0-0
	Plastic	10	10	41(+95)	1(±1)	1	0	0-306	0-1
	Overall	**28**	**28**	**53(±100)**	2(±9)	**3**	0	**0->400**	0-43
Aug. 2012	**HRW system**	**n-raw**	***n-treated***	***Mean-raw***	***mean-treated***	***Median-raw***	***median-treated***	***Range-raw***	***Range-treated***
	Catchment	8	5	128 (±122)	18(± 15)	108	18	7-332	0-39
	Concrete	8	9	200 (± 222)	3(± 8)	121	0	1->400	0-23
	Metallic	15	15	108 (±192)	3(±9)	29	0	0->400	0-33
	Plastic	10	10	143 (± 318)	1(±3)	14	0	1-345	0-10
	Overall	**41**	**39**	**110(±148)**	**5(±10)**	**29**	**0**	**0->400**	**0-39**

***highlighted: SODIS treated water, n-number of samples. N/A-Not applicable (sample size was only one system), mean value (±standard deviation)**

Appendix 10: Faecal enterococci contamination levels in CFU/100ml in raw HRW systems and the SODIS treatment efficiencies during the different months in the year

Month/ Year	HRW system	Sample size		*Mean*		*Median*		*Range*	
Aug.2011		**Raw**	**Treated**	**Raw**	**Treated**	**Raw**	**Treated**	**Raw**	**Treated**
	Catchment	5	4	242(± 216)	10(±20)	>400	0	2->400	0-39
	Concrete	10	9	50(± 124)	1(±1)	2	0	0->400	0-1
	Metallic	16	17	148(+177)	2(±7)	53	0	0->400	0-28
	Plastic	10	10	92 (±188)	40(±126)	11	0	0->400	0->400
	Overall	**41**	**40**	**122(±173)**	11 (± 63)	**11**	0	**0->400**	0->400
Sept. 2011	**HRW system**	**n-raw**	***n-treated***	***Mean-raw***	***mean-treated***	***median-raw***	***median-treated***	***Range-raw***	***Range-treated***
	Catchment	6	6	200 (± 219)	1(±2)	200	0	0->400	0-5
	Concrete	11	10	173 (±185)	41(±126)	48	0	0->400	0->400
	Metallic	18	18	119 (±159)	0(±1)	38	0	0->400	0-4
	Plastic	9	10	111 (±166)	0(±0)	39	0	0->400	0-0
	Overall	**44**	**44**	**143(±171)**	7(±60)	**48**	0	**0->400**	0->400
Oct. 2011	**HRW system**	**n-raw**	***n-treated***	***Mean-raw***	***mean-treated***	***median-raw***	***median-treated***	***Range-raw***	***Range-treated***
	Catchment	8	8	71 (±143)	0(±0)	4	0	0->400	0-1
	Concrete	9	9	35 (±46)	0(±0)	10	0	0-121	0-0
	Metallic	16	16	76 (±138)	0(±0)	13	0	0->400	0-1
	Plastic	11	11	14 (±14)	0(±0)	10	0	0-38	0-0
	Overall	**44**	**44**	**51(±105)**	0(±0)	**8**	0	0->400	0-0

Nov.2011	HRW system	n-raw	*n-treated*	*Mean-raw*	*mean-treated*	*median-raw*	*median-treated*	*Range-raw*	*Range-treated*
	Catchment	8	8	74 (±136)	3(±7)	26	0	0->400	0-21
	Concrete	10	10	81 (± 81)	1(±1)	61	0	0-216	0-1
	Metallic	18	18	49 (± 62)	1(±0)	35	0	0-264	0-2
	Plastic	11	11	15 (± 16)	1(±1)	4	0	0-38	0-0
	Overall	**47**	**47**	**52(±78)**	**1(±3)**	**24**	0	0->400	0-21
Dec. 2011	**HRW system**	**n-raw**	***n-treated***	***Mean-raw***	***mean-treated***	***median-raw***	***median-treated***	***Range-raw***	***Range-treated***
	Catchment	8	8	19 (±26)	1(±0)	13	0	1-79	0-2
	Concrete	11	11	18 (±23)	1(±1)	12	0	0-80	0-1
	Metallic	18	18	138 (± 182)	1(±1)	21	0	0->400	0-4
	Plastic	11	11	52 (±119)	0(±1)	9	0	0->400	0-0
	Overall	**48**	**48**	**71(±135)**	0(±1)	**14**	0	0->400	0-4
Jan. 2012	**HRW system**	**n-raw**	***n-treated***	***Mean-raw***	***mean-treated***	***median-raw***	***median-treated***	***Range-raw***	***Range-treated***
	Catchment	6	6	47 (± 64)	0(±0)	13	0	0-157	0-0
	Concrete	10	10	172 (± 172)	0(±0)	76	0	0->400	0-0
	Metallic	13	13	6 (±12)	0(±0)	10	0	0-271	0-0
	Plastic	11	11	63 (±63)	0(±0)	4	0	0->400	0-0
	Overall	**40**	**40**	**80(±127)**	0(±0)	**12**	0	0->400	0-0

Feb.2012	**HRW system**	**n-raw**	***n-treated***	***Mean-raw***	***mean-treated***	***median-raw***	***median-treated***	***Range-raw***	***Range-treated***
	Catchment	1	1	1 (±N/A)	0(±N/A)	1	0	1-1	0-0
	Concrete	4	4	114 (±191)	0(±0)	27	0	2->400	0-0
	Metallic	8	9	3 (± 6)	1(±N/A)	0	0	0-13	0-1
	Plastic	6	6	4 (± 8)	0 (±0)	0	0	0-20	0-0
	Overall	**19**	**20**	**27(±91)**	0(±0)	**0**	0	**0->400**	0-0
Mar. 2012	**HRW system**	**n-raw**	***n-treated***	***Mean-raw***	***mean-treated***	***median-raw***	***median-treated***	***Range-raw***	***Range-treated***
	Catchment	2	2	243 (±253)	0(±0)	243	0	64->400	0-0
	Concrete	11	11	186 (± 194)	2(±6)	90	0	0->400	0-19
	Metallic	8	8	64 (±108)	0(±0)	0	0	0-250	0-0
	Plastic	9	9	15 (± 18)	1(±1)	8	0	0-55	0-4
	Overall	**30**	**30**	**102(±151)**	1(±4)	**19**	0	0->400	0-19
Apr. 2012	**HRW system**	**n-raw**	***n-treated***	***Mean-raw***	***mean-treated***	***median-raw***	***median-treated***	***Range-raw***	***Range-treated***
	Catchment	8	8	175 (± 232)	12(±33)	6	0	0->400	0-93
	Concrete	9	9	108 (±141)	0(±0)	6	0	0-326	0-0
	Metallic	17	17	72 (±99)	6(±14)	15	0	0-319	0-54
	Plastic	9	9	76 (±106)	0(±0)	7	0	0-259	0-0
	Overall	**43**	**43**	**64(±126)**	5(±17)	7	0	0->400	0-93

Jun. 2012	HRW system	n-raw	*n-treated*	*Mean-raw*	*mean-treated*	*median-raw*	*median-treated*	*Range-raw*	*Range-treated*
	Catchment	6	6	47 (± 10)	0(±0)	47	0	47-47	0-0
	Concrete	9	9	25 (± 83)	0(±0)	6	0	0-116	0-0
	Metallic	15	15	25 (±51)	1(±2)	0	0	0-134	0-6
	Plastic	8	8	2 (± 24)	1(±1)	1	0	0-13	0-4
	Overall	**38**	**38**	**31(±54)**	0(±1)	**5**	0	**0-256**	0-6
July 2012	**HRW system**	**n-raw**	***n-treated***	***Mean-raw***	***mean-treated***	***median-raw***	***median-treated***	***Range-raw***	***Range-treated***
	Catchment	1	1	47 (±N/A)	0(±N/A)	47	0	47-47	0-0
	Concrete	8	8	25 (± 40)	0(±0)	6	0	0-116	0-0
	Metallic	9	9	25 (± 51)	0(±0)	0	0	0-134	0-0
	Plastic	10	10	2 (± 4)	0(±0)	1	0	0-13	0-0
	Overall	**28**	**28**	**17(±37)**	0(±0)	**1**	0	**0-134**	0-0
Aug. 2012	**HRW system**	**n-raw**	***n-treated***	***Mean-raw***	***mean-treated***	***median-raw***	***median-treated***	***Range-raw***	***Range-treated***
	Catchment	8	5	63 (± 102)	1(±2)	8	0	0-255	0-4
	Concrete	8	9	145 (±170)	1(±1)	49	0	0->400	0-1
	Metallic	15	15	79 (±112)	6(±24)	33	0	0->400	0-94
	Plastic	10	10	93(±121)	1(±1)	42	0	0->400	0-2
	Overall	**41**	**39**	**94(±125)**	3(±15)	**37**	0	0->400	**0-94**

***highlighted: SODIS treated water, n-number of samples. N/A-Not applicable (sample size was only one system), mean value (±standard deviation)**

Appendix 11: Percentage of raw and SODIS treated HRW samples contaminated with *E. coli* according to different systems during the different months of the study

MONTH/ YEAR	HRW system	*Raw HRW*			*Treated*		
Aug. 2011		**n**	***No (%)contaminated***	***No (%) potable***	***n***	***No (%) contaminated***	***No (%) potable***
	Catchment	5	5 (100%)	0 (0%)	4	2 (50%)	2 (50%)
	Concrete	10	7 (70%)	3 (30%)	9	2 (22%)	7 (78%)
	Metallic	16	9(56%)	7 (44%)	17	5 (29%)	12 (71%)
	Plastic	10	7 (70%)	3 (30%)	10	3 (30%)	7 (70%)
	Overall	**41**	**28(68%)**	**13 (32%)**	**40**	12 (30%)	**28 (70%)**
Sept. 2011	**HRW system**	**n**	***No (%) contaminated***	***No (%) potable***	***n***	***No (%) contaminated***	***No (%) potable***
	Catchment	6	5 (83%)	1 (17%)	6	1 (17%)	5 (83%)
	Concrete	11	9 (82%)	2 (18%)	10	1 (10%)	9 (90%)
	Metallic	18	12 (67%)	6 33%)	18	2 (11%)	16 (89%)
	Plastic	9	4 (44%)	5 (56%)	10	0 (0%)	10 (100%)
	Overall	**44**	**30(68%)**	**14 (32%)**	**44**	**4 (9%)**	**40 (91%)**
Oct. 2011	**HRW system**	**n**	***No (%) contaminated***	***No (%) potable***	***n***	***No (%) contaminated***	***No (%) potable***
	Catchment	8	5 (63%)	3 (37%)	8	0 (0%)	8 (100%)
	Concrete	9	6(67%)	3 (33%)	9	2 (22%)	7(78%)
	Metallic	16	8(50%)	8 (50%)	16	4 (25%)	12 (75%)
	Plastic	11	5(45%)	6 (55%)	11	2 (18%)	9 (82%)
	Overall	**44**	**24(55%)**	**20(45%)**	**44**	**8(18%)**	**36 (82%)**

Nov. 2011	**HRW system**	n	*No (%) contaminated*	*No (%) potable*	*n*	*No (%) contaminated*	*No (%) potable*
	Catchment	8	7 (88%)	1 (12%)	8	1 (13%)	7 (87%)
	Concrete	10	8 (80%)	2 (20%)	10	3 (30%)	7 (70%)
	Metallic	18	14 (78)	4 (22%)	18	5 (28%)	13(72%)
	Plastic	11	5 (45%)	6 (55%)	11	2 (18%)	9 (82%)
	Overall	**47**	**34(72%)**	**13(28%)**	**47**	**11 (23%)**	**36 (77%)**
Dec. 2011	**HRW system**	**n**	*No (%) contaminated*	*No (%) potable*	*n*	*No (%) contaminated*	*No (%) potable*
	Catchment	8	6(75%)	2 (25%)	8	0(0%)	8 (100%)
	Concrete	11	6(55%)	5 (45%)	11	2 (18%)	9 (82%)
	Metallic	18	10(56%)	8 (44%)	18	2 (11%)	16 (89%)
	Plastic	11	2(18%)	9 (82%)	11	0 (0%)	11 (100%)
	Overall	**48**	**24(50%)**	**24 (50%)**	**48**	**4 (8%)**	**44 (92%)**
Jan. 2012	**HRW system**	**n**	*No (%) contaminated*	*No (%) potable*	*n*	*No (%) contaminated*	*No (%) potable*
	Catchment	6	5 (83%)	1 (17%)	6	2 (33%)	4 (67%)
	Concrete	10	7 (70%)	3 (30%)	10	1 (10%)	9 (90%)
	Metallic	13	9(69%)	4 (31%)	13	0 (0%)	13 (100%)
	Plastic	11	7(64%)	4 (36%)	11	0 (0%)	11 (100%)
	Overall	**40**	**28(70%)**	**12(30%)**	**40**	**3 (8%)**	**37 (92%)**
Feb. 2012	**HRW system**	**N**	*No (%) contaminated*	*No (%) potable*	*n*	*No (%) contaminated*	*No (%) potable*
	Catchment	1	0 (0%)	1 (100%)	1	0 (0%)	1(100%)
	Concrete	4	2(50%)	2 (50%)	4	0 (0%)	4 (100%)
	Metallic	8	1 (13%)	7 (87%)	9	0 (0%)	9 (100%)
	Plastic	6	1 (17%)	5 (83%)	6	0 (0%)	6 (100%)
	Overall	**19**	**4(21%)**	**15(79%)**	**20**	0 (0%)	**20 (100%)**

Mar. 2012	**HRW system**	**N**	*No (%) contaminated*	*No (%) potable*	*n*	*No (%) contaminated*	*No (%) potable*
	Catchment	2	2 (100%)	0 (0%)	2	0 (0%)	2 (100%)
	Concrete	11	8 (73%)	3 (27%)	11	3 (27%)	8 (77%)
	Metallic	8	4 (50)	4 (50%)	8	1 (13%)	7 (87%)
	Plastic	9	4 (44%)	5 (56%)	9	0 (0%)	9 (100%)
	Overall	**30**	**18(60%)**	**12(40%)**	**30**	**4 (10%)**	**26 (90%)**
Apr. 2012	**HRW system**	**N**	*No (%) contaminated*	*No (%) potable*	*n*	*No (%) contaminated*	*No (%) potable*
	Catchment	8	8(100%)	0 (0%)	8	1 (13%)	7 (87%)
	Concrete	9	8(89%)	1 (11%)	9	1 (11%)	8 (89%)
	Metallic	17	13(76%)	4 (24%)	17	2 (12%)	15(88%)
	Plastic	9	6(67%)	3 (33%)	9	1 (11%)	8(89%)
	Overall	**43**	**35(81%)**	**8(19%)**	**43**	**5 (12%)**	**38(88%)**
June 2012	**HRW system**	**N**	*No (%) contaminated*	*No (%) potable*	*n*	*No (%) contaminated*	*No (%) potable*
	Catchment	6	5 (83%)	1 (17%)	6	0 (0%)	6 (100%)
	Concrete	9	7 (78%)	2 (22%)	9	1 (11%)	8(89%)
	Metallic	15	11 (73%)	4 (27%)	15	5 (33%)	10(67%)
	Plastic	8	5 (63%)	3 (37%)	8	1 (13%)	7 (87%)
	Overall	**38**	**28(74%)**	**10(26%)**	**38**	**7 (18%)**	**31 (82%)**
July 2012	**HRW system**	**N**	*No (%) contaminated*	*No (%) potable*	*n*	*No (%) contaminated*	*No (%) potable*
	Catchment	1	1 (100%)	0 (0%)	1	0 (0%)	1 (100%)
	Concrete	8	5(63%)	3 (37%)	8	3 (38%)	5 (62%)
	Metallic	9	7 (78%)	2(22%)	9	0 (0%)	9 (100%)
	Plastic	10	7 (70%)	3 (30%)	10	2 (20%)	**8 (80%)**
	Overall	**28**	**20(71%)**	**8(29%)**	**28**	**5 (18%)**	**23 (82%)**

Aug. 2012	HRW system	N	*No (%) contaminated*	*No (%) potable*	*n*	*No (%) contaminated*	*No (%) potable*
	Catchment	8	8 (100%)	0 (0%)	5	4 (80%)	1 (20%)
	Concrete	8	8 (100%)	0 (0%)	9	3 (33%)	6 (67%)
	Metallic	15	14 (93%)	1 (7%)	15	4 (27%)	11 (73%)
	Plastic	10	6 (67%)	4 (33%)	10	2 (20%)	8 (80%)
	Overall	**41**	**36(88%)**	**5 (12%)**	**39**	**13 (33%)**	**26 (66%)**

* contaminated water-with more than zero cfu of *E. coli* /100ml leave one colum of portable

Appendix 12: Percentage of raw and SODIS treated HRW samples contaminated with faecal enterococci according to different systems

MONTH/ YEAR		Raw HRW			Treated HRW		
Aug. 2011	**System**	**N**	*No (%) contaminated*	*No (%) potable*	*n*	*No (%) contaminated*	*No (%) potable*
	Catchment	5	5(100%)	0 (100%)	4	1 (25%)	3 (75%)
	Concrete	10	8(80%)	2 (20%)	9	1 (11%)	8 (89%)
	Metallic	16	14(88%)	2 (12%)	17	4 (24%)	13 (76%)
	Plastic	10	9 (90%)	1 (10%)	10	1 (10%)	9 (90%)
	Overall	**41**	**36 (88%)**	**5(12%)**	**40**	**7 (18%)**	**33 (82%)**
Sept. 2011	**HRW system**	**N**	*No (%) contaminated*	*No (%) potable*	*n*	*No (%) contaminated*	*No (%) potable*
	Catchment	6	3(50%)	3 (5%)	6	1 (17%)	5(83%)
	Concrete	11	9(82%)	2 (18%)	10	3 (30%)	7 (70%)
	Metallic	18	15(83%)	3 (17%)	18	2 (11%)	16 (89%)
	Plastic	9	7(78%)	2 (22%)	10	0 (0%)	10 (100%)
	Overall	**44**	**34(77%)**	**10 (23%)**	**44**	6 (14%)	**38 (86%)**
Oct. 2011	**HRW system**	**N**	*No (%) contaminated*	*No (%) potable*	*n*	*No (%) contaminated*	*No (%) potable*
	Catchment	8	7(88%)	1(12%)	8	1 (13%)	7 (87%)
	Concrete	9	7(78%)	2 (22%)	9	0 (0%)	9 (100%)
	Metallic	16	12(75%)	4(25%)	16	1 (6%)	15 (94%)
	Plastic	11	8(73%)	3(27%)	11	0 (0%)	11 (100%)
	Overall	**44**	**34(77%)**	**10(23%)**	**44**	**2 (5%)**	**42(95%)**

Nov. 2011	**HRW system**	**N**	*No (%) contaminated*	*No (%) potable*	*n*	*No (%) contaminated*	*No (%) potable*
	Catchment	8	6(75%)	2 (25%)	8	1(13%)	7 (87%)
	Concrete	10	9(90%)	1(10%)	10	1 (10%)	9 (90%)
	Metallic	18	16(89%)	2 (11%)	18	2 (11%)	16 (89%)
	Plastic	11	9(82%)	2 (18%)	11	0 (0%)	11 (100%)
	Overall	47	**40 (85%)**	**7(15%)**	**47**	**4 (9%)**	**43 (91%)**
Dec. 2011	**HRW system**	**N**	*No (%) contaminated*	*No (%) potable*	*n*	*No (%) contaminated*	*No (%) potable*
	Catchment	8	8(100%)	0 (0%)	8	2 (25%)	6 (75%)
	Concrete	11	9(82%)	2 (18%)	11	2 (18%)	9 (82%)
	Metallic	18	15(83%)	3(17%)	18	6 (33%)	12 (67%)
	Plastic	11	9(82%)	2(18%)	11	0 (0%)	11 (100%)
	Overall	**48**	**41(85%)**	**7(15%)**	**48**	**10(21%)**	**38 (79%)**
Jan. 2012	**HRW system**	**N**	*No (%) contaminated*	*No (%) potable*	*n*	*No (%) contaminated*	*No (%) potable*
	Catchment	6	5(83%)	1 (17%)	6	0 (0%)	6 (100%)
	Concrete	10	8(80%)	2 (20%)	10	0 (0%)	10 (100%
	Metallic	13	12(92%)	1(8%)	13	0 (0%)	13 (100%)
	Plastic	11	10(91%)	1 (9%)	11	0 (0%)	11 (100%)
	Overall	**40**	**35(88%)**	**5 (12%)**	**40**	**0 (0%)**	**40(100%)**
Feb. 2012	**HRW system**	**N**	*No (%) contaminated*	*No (%) potable*	*n*	*No (%) contaminated*	*No (%) potable*
	Catchment	1	1(100%)	0 (0%)	1	0 (0%)	1 (100%)
	Concrete	4	4(100%)	0 (0%)	4	0 (0%)	4 (100%)
	Metallic	8	2(25%)	6 (75%)	9	1 (11%)	8 (89%)
	Plastic	6	2(33%)	4(67%)	6	0 (%)	6 (100%)
	Overall	**19**	**9(42%)**	**10(58%)**	**20**	**1(5%)**	**19 (95%)**

Mar. 2012	HRW system	N	*No (%) contaminated*	*No (%) potable*	*n*	*No (%) contaminated*	*No (%) potable*
	Catchment	2	2(100%)	0 (0%)	2	0 (0%)	2 (100%)
	Concrete	11	10(91%)	1 (9%)	11	1 (9%)	10 (91%)
	Metallic	8	3(38%)	5 (62%)	8	0 (0%)	8 (100%)
	Plastic	9	7(78%)	2 (22%)	9	1 (11%)	8 (91%)
	Overall	**30**	**22(73%)**	**8 (27%)**	**30**	**2(7%)**	**28(93%)**
Apr. 2012	**HRW system**	**N**	***No (%) contaminated***	***No (%) potable***	***n***	***No (%) contaminated***	***No (%) potable***
	Catchment	8	7(88%)	1 (12%)	8	1 (13%)	7 (87%)
	Concrete	9	8(89%)	1 (11%)	9	0 (0%)	9 (100%)
	Metallic	17	14(83%)	3(17%)	17	4 (24%)	13 (76%)
	Plastic	9	7(78%)	2 (22%)	9	0 (0%)	9 (100%)
	Overall	**43**	**36(84%)**	**7(16%)**	**43**	**5 (12%)**	38 (88%)
June 2012	**HRW system**	**N**	***No (%) contaminated***	***No (%) potable***	***n***	***No (%) contaminated***	***No (%) potable***
	Catchment	6	4(67%)	2 (33%)	6	0 (0%)	6 (100%)
	Concrete	9	3(33%)	6 (67%)	9	0 (0%)	9 (100%)
	Metallic	15	11(73%)	4 (27%)	15	3 (20%)	12 (80%)
	Plastic	8	5(63%)	3 (37%)	8	1 (13%)	7 (87%)
	Overall	**38**	**23(61%)**	**15(39%)**	**38**	**5 (11%)**	33 (89%)
July 2012	**HRW system**	**N**	***No (%) contaminated***	***No (%) potable***	***n***	***No (%) contaminated***	***No (%) potable***
	Catchment	1	1(100%)	0 (0%)	1	0 (0%)	1 (100%)
	Concrete	8	7(88%)	1 (12%)	8	0 (0%)	8 (100%)
	Metallic	9	7(78%)	2 (22%)	9	0 (0%)	9 (100%)
	Plastic	10	5(50%)	5(50%)	10	0 (0%)	10 (100%)
	Overall	**28**	**20(71%)**	**8(29%)**	**28**	**0 (0%)**	28 (100%)

Aug. 2012	**HRW system**	**N**	***No (%) contaminated***	***No (%) potable***	***n***	***No (%) contaminated***	***No (%) potable***
	Catchment	8	5(83%)	3(17%)	5	1 (20%)	4 (80%)
	Concrete	8	7(88%)	1(12%)	9	1 (11%)	10 (89%)
	Metallic	15	11(73%)	4 (27%)	15	2 (13%)	13 (87%)
	Plastic	10	8(80%)	2(20%)	10	2 (20%)	8 (80%)
	Overall	**41**	**31(76%)**	**10(24%)**	**39**	**6 (15%)**	33 (85%)

* contaminated water-with more than zero cfu of faecal enterococci/100ml